Hindawi Publishing Corporation
Active and Passive Electronic Components
Volume 2007, Article ID 30946, 13 pages
doi:10.1155/2007/30946

Review Article

Plasmonics: Manipulating Light at the Subwavelength Scale

Cheng-Ping Huang and Yong-Yuan Zhu

National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, China

Received 21 August 2007; Accepted 10 October 2007

Recommended by Yalin Lu

The coupling of light to collective oscillation of electrons on the metal surface allows the creation of surface plasmon-polariton wave. This surface wave is of central interest in the field of plasmonics. In this paper, we will present a brief review of this field, focusing on the plasmonic waveguide and plasmonic transmission. In the plasmonic waveguide, the light can be guided along the metal surface with subwavelength lateral dimensions, enabling the possibility of high-density integration of the optical elements. On the other hand, in the plasmonic transmission, the propagation of light through a metal surface can be tailored with the subwavelength holes, leading to the anomalous transmission behaviors which have received extensive investigations in recent years. In addition, as a supplement to plasmonics in the visible and near-infrared region, the study of THz plasmonics has also been discussed.

1. INTRODUCTION

Microelectronics based on semiconductors and integrated circuits has been well developed, which constructs a strong fundament for various applications, especially the information processing and transmission. However, further development demanded by the information transmission is always limited by the performance of electronic components as, for example, less data can be carried by the electrons. As an alternative, photonics employing the photons as the information carrier may offer a solution to this problem, where the photons travel faster with a larger information capacity. Compared with the electronic counterpart, unfortunately, the conventional photonic components such as the optical fiber are bulky in size (due to the diffraction limit of light), thus setting a great limit to the optical integration. This point holds, even for the photonic crystal, because the period and size of the photonic crystal are usually on the order of the electromagnetic wavelength.

Recently, it has been shown that the trade-off between the capacity and size mentioned above can be overcome by using the surface plasmon-based photonics or plasmonics. The key point is that the electromagnetic wave, which usually travels in a dielectric waveguide, can propagate along the metal surface in the form of surface plasmon-polariton (SPP) mode [1]. As a consequence, the fields can be strongly confined to the metal surface with the lateral dimensions much smaller than the wavelength. Therefore, plasmonic circuits possess both the capacity of photonics and miniaturization of electronics, opening a new way for the future applications [2].

Current interest in plasmonics is, actually, not limited to the investigation of plasmonic circuits. Some novel metallic structures and phenomena, such as the enhanced light transmission through perforated metal films, have also attracted much attention [3, 4], where the SPP modes are usually involved. By employing the highly enhanced plasmon field, a significant enhancement of Raman signal, molecular fluorescence, and nonlinear frequency conversion has been reported [5–7]. And by using the sensitivity of SPP mode to the environment, highly sensitive biosensors can be constructed [8]. Furthermore, plasmonics can also find its potential applications in plasmonic light sources, plasmonic nanolithography, and so on [9, 10].

Here, we review the progress in plasmonics, focusing on the plasmonic waveguide and plasmonic transmission. The paper is organized as follows. In Section 2, we give a simple introduction to the plasmon polariton. In Section 3, the plasmonic waveguide based on various configurations is presented, including the line defect created in periodic metal surface, metal stripe or nanowire, arrays of nanoparticles, and gap waveguide. Employing the gain media to compensate the propagation loss is also mentioned. In Section 4, the plasmonic transmission in various metallic systems, such as a single hole/slit in a metal film, a single hole/slit surrounded by surface corrugations, and subwavelength hole arrays, has been discussed. And in Section 5, plasmonics of THz frequencies is reviewed, concerning about THz metamaterials, THz SPP mode, and waveguiding in various structures, as well as the THz transmission. A short summary is provided in Section 6.

2. PLASMON POLARITON

It is stressed here that it is the metal rather than the dielectric that plays a more important role in the plasmonics. The difference of metal from dielectric lies in not only electrical but also optical properties. In the metal, the presence of huge free electrons gives rise to a unique dielectric response described by the Drude model

$$\varepsilon_m = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)}. \tag{1}$$

Here, ω_p is the bulk plasma frequency and γ is the scattering rate of the electrons. For the convenience of discussion, we can neglect the damping of the metal ($\gamma = 0$). It is now clear that when $\omega > \omega_p$, the permittivity is positive and the light can propagate through the metal (with a dispersion relation $\omega^2 = \omega_p^2 + c^2k^2$). This propagating mode, which essentially involves the coupling between light and bulk free electrons, can be termed the bulk plasmon polariton (BPP). Conversely when $\omega < \omega_p$, which is usually satisfied in the considered frequency range, the permittivity is then negative and the light propagation in the metal is forbidden.

It is interesting to find that, even when the permittivity of metal is negative, the propagation of light can be allowed, but in the form of a surface wave on the metal. This is the so-called SPP mode mentioned above. To get knowledge about the character of SPP mode, we take the typical configuration of infinite metal/dielectric interface as an example (see Figure 1). The interaction between light and surface free charges yields, in this case, the following dispersion relation [11]:

$$k_{\text{spp}} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}. \tag{2}$$

Here, ε_d is the permittivity of dielectric. Notice that, to make k_{spp} real, we have $\varepsilon_m + \varepsilon_d < 0$, and thus $\omega < \omega_{\text{sp}} \equiv \omega_p/\sqrt{1+\varepsilon_d}$, where ω_{sp} is the surface plasmon frequency. This is the frequency range for the existence of this surface mode. For convenience, the dispersion relation of BPP and SPP modes has been plotted schematically in Figure 1. Here, we summarize some features of SPP mode on the flat metal/dielectric interface as follows.

(1) The SPP mode is an electromagnetic wave coupled with the surface electron-density oscillations. The magnetic field of the mode is parallel to the metal surface and perpendicular to the propagation direction (TM mode). Instead, the electric field has both the normal ($E_\perp$) and tangent ($E_{//}$) components. On the dielectric side, $E_\perp/E_{//} = \sqrt{\varepsilon_m/\varepsilon_d}$; on the metal side, $E_\perp/E_{//} = -\sqrt{\varepsilon_d/\varepsilon_m}$. Thus, when the frequency is well below the plasma frequency, the electric field inside the metal is mainly tangent and the electrons move back and forth in the propagation direction, forming a longitudinal electron-density wave.

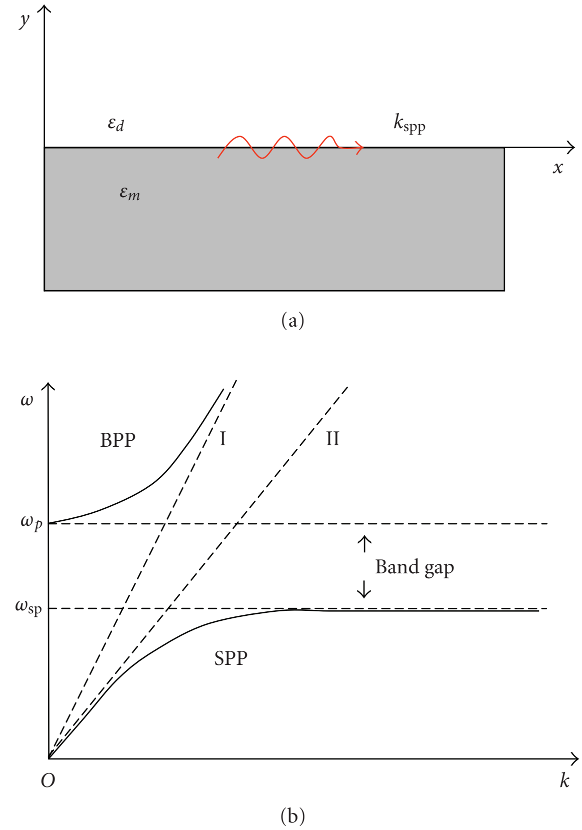


FIGURE 1: Plasmon-polariton mode associated with the metals: (a) schematic view of infinite metal/dielectric interface; (b) dispersion relation of bulk plasmon-polariton (BPP) and surface plasmon-polariton (SPP) modes. The dashed lines I and II denote the light dispersion $\omega = ck$ and , $\omega = ck/\sqrt{\varepsilon_d}$, respectively. The frequency range between ω_{sp} and ω_p corresponds to a gap where the electromagnetic wave cannot propagate via either bulk or surface modes.

(2) The SPP mode can propagate along the metal surface with a larger propagation constant ($k_{\text{spp}} > k_0\sqrt{\varepsilon_d}$). This means a reduced wavelength as well as a smaller propagation velocity of the electromagnetic wave. Considering of the absorption of the metal, however, the propagation length of SPP mode is finite. A detailed calculation shows that the energy propagation length can be expressed as $L_{\text{spp}} \approx \varepsilon_m'^2/k_0\varepsilon_m''\varepsilon_d^{3/2}$, where ε_m' and ε_m'' are, respectively, the real and imaginary parts of permittivity of the metal. In the visible and near-infrared region, L_{spp} is from several to hundreds of micrometers.

(3) The SPP mode is evanescent on either side of the interface due to the larger propagation constant. On the dielectric side, the decaying length of the field is $\delta_d \approx \sqrt{|\varepsilon_m'|}/k_0\varepsilon_d$; on the other side, the decaying length is $\delta_m \approx 1/k_0\sqrt{|\varepsilon_m'|}$. For the interface comprised by silver and glass and free-space wavelength of 800 nm, for example, the obtained decaying lengths are about 300 nm and 25 nm, respectively. This suggests that the wave is strongly confined to the metal surface,

which is just desired in practice. Note that a strong enhancement of fields near the surface can also be achieved.

Due to the larger propagation constant, the SPP mode cannot be excited directly by the incident light. To compensate the wavevector or phase mismatch between the SPP mode and incident light, some special techniques have been introduced [11], such as prism coupling or attenuated total reflection, waveguide coupling using an optical fiber, grating coupling employing the light diffraction, and near-field excitation with a near-field optical microscopy. In addition, a single surface defect, such as surface protuberance and subwavelength hole or slit, may act as an efficient source for the SPP mode [11–13], where some diffraction component or other can ensure the momentum conservation. On the other hand, a direct observation of SPP mode is relatively difficult because of its localized feature. This can be addressed with the use of near-field optical microscopy [14]. It is worthy of noticing that, by structuring the metal surface with nanoscale corrugations, the SPP mode will be scattered and some photons can escape from the surface. Thus the SPP mode can be mapped by recording the scattered light [15]. Recently, a method called fluorescence imaging has been proposed to observe the SPP mode [16], where the metal surface is covered with the fluorescence molecules which emit the radiation with the intensity proportional to the surface electric field. With this method, the reflection, beam splitting, and interference of SPP mode have been successfully observed [17].

It is mentioned that, besides the flat metal/dielectric interface, the SPP mode can also exists in other configurations with some parallel characteristics. As an example, in a thin metal film with the thickness typically of the skin depth, the SPP modes on both sides will couple strongly to each other, giving rise to a long-range SPP mode [18]. In addition, the current research interest in plasmon polariton has been extended from SPP to particle plasmon polariton, where the dimensions of metallic particle are much smaller than the electromagnetic wavelength. A detailed discussion on this topic can be found in [19].

3. PLASMONIC WAVEGUIDE

Plasmonic circuit chip would have the ability to have the plasmonic signal generation, transport, modulation, detection, and so forth integrated. And plasmonic waveguide is one of the most important components of plasmonic chip, with which the optical signal can be sent from one section to another. In practice, both smallness of mode profile and largeness of propagation length (or low propagation loss) are desired for a plasmonic waveguide. Although the light can be guided along a planar metal/dielectric interface, the confinement offered is only one-dimensional. Thus different configurations of waveguide have been proposed and investigated.

One method is to employ the plasmonic bandgap effect at the metal surface, with the underlying physics similar to that of a photonic crystal. This is achieved by corrugating the metal surface with the periodic protuberance and creating a line defect. Within a certain wavelength region, the SPP mode can propagate along the line channel but is prohibited from traveling in the periodic structure. With this method, Bozhevolnyi et al. have directly demonstrated the SPP guiding at the wavelength of 782 nm, where 200 nm-wide and 45 nm-high gold scatterers arranged in a triangular lattice of period 400 nm were employed [20]. For a 3.2 μm-wide line channel, the propagation length of SPP mode is found to be more than 18 μm. However, the propagation length will be drastically reduced when decreasing the channel width. This trade-off between mode size and propagation length is a basic feature of the plasmonic waveguide. In addition, the waveguiding, in this way, has also been realized at the telecom wavelength 1500 nm recently [21].

The second method is to use the metal stripe or nanowire as the plasmonic waveguide. A metal stripe embedded in a homogeneous dielectric is able to support ultralong-range SPP mode when both thickness and width of the metal film are properly selected (here, the width is much larger than the film thickness) [22]. At the wavelength 1550 nm, the experimentally reported propagation length for the silver waveguide is up to 13.6 mm [23]. This huge propagation length is, however, accompanied by a poor confinement of the mode, which has a spread of several micrometers in lateral dimensions. It is interesting to note that, although the long-range SPP mode is difficult to obtain with a metal stripe embedded in an asymmetric environment [24], a thin metal film sandwiched between a one-dimensional photonic crystal and an arbitrary medium can give rise to a long-range propagation of SPP mode of several millimeters [25]. On the other hand, the metallic nanowire (the width and thickness are both subwavelength) placed on the substrate can also be used to guide the light. Experimentally, a 200 nm-wide and 50 nm-thick gold wire has been fabricated and the propagation of SPP mode locally excited at the wavelength of 800 nm investigated [26]. The results show that the SPP mode is confined to a lateral extension even smaller than the width of nanowire (the full width at half-maximum of the mode is only 115 nm), thus demonstrating waveguiding on a scale below the diffraction limit. This characteristic is useful for realizing high-density integration of the photonic devices. Nonetheless, the subwavelength confinement of metallic nanowire yields a greatly reduced propagation length, which is typically of a few micrometers [26, 27]. Note that the long-range SPP mode also exists in the nanowire with a huge mode size when buried in a dielectric [28].

Cutting the nanowire into nanoparticles provides a third method for the plasmonic waveguiding. In the nanoparticle, an oscillating electric dipole moment can be resonantly excited by the incident light, setting up the particle plasmon-polariton resonance with the fields greatly enhanced and well confined to the particle. The resonance frequency is dependent on the particle shape and size. It was proposed that, when the particles are arranged in a linear chain with the subwavelength particle interspaces, electromagnetic energy transport below the diffraction limit can be reached via near-field coupling along the particle chain [29]. The theoretical prediction has been confirmed experimentally with the waveguide structure consisting of rod-shaped silver particles, where the waveguide was excited by the scan tip of a near-field microscope and energy transport probed with the fluorescent nanospheres [30]. In this way, a small attenuation length of several hundred nanometers, as a result of high confinement of the fields, has been determined (the source wavelength is 570 nm). The propagation length can be substantially enlarged by using another waveguide structure, which is composed of two-dimensional particle arrays patterned on a silicon wafer [31]. To achieve the transverse confinement along the waveguide plane, a special design of the particle size has been adopted, that is, the particle size is reduced gradually from the center of waveguide to both edges. The plasmon fields are, indeed, concentrated near the waveguide center, showing a lateral confinement of the wavelength scale. Simultaneously, corresponding to the excitation wavelength of 1500 nm, a larger propagation length over 50 μm has been resulted. It is worthy of mentioning that the energy transport along a linear chain can also be accomplished by employing the magnetic plasmon polariton and split ring resonators [32], where the magnetic rather than electric field interacts strongly with the magnetic dipole moment or electron oscillations taking the form of conduction current in the metallic ring resonators.

Gap waveguide presents another scheme promising for the SPP waveguiding, where the mode is localized in the dielectric region surrounded by the metallic walls. Since the penetration length of electromagnetic fields into the metal is only of the skin depth, the mode profile is mainly determined by the size of dielectric gap. One simple example of gap waveguide is the subwavelength slit, in which the SPP modes on both metal surfaces will be coupled. To obtain two-dimensional confinement, the slit structures can be modified to V-shaped grooves. Numerical simulations has pointed out that, in such a groove, channel plasmon-polariton (CPP) mode confined to the bottom of groove could be supported with a low propagation loss [33]. Recently, V-shaped grooves have been milled into a metal and measurements have confirmed the existence of CPP mode [34]. For a groove with the width 600 nm and depth 1000 nm (the groove angle is about 25°), the propagation length is varying between 90 and 250 μm relying on the wavelength used (1425~1620 nm). Correspondingly, the full width at half-maximum of the mode is reported to be ~1150 nm, which is subwavelength but larger than the groove width, showing that the CPP mode spreads out of the groove significantly. Using this geometry, various waveguide components, including splitters, interferometers, and ring resonators, have been constructed [35].

Besides the aforementioned semiclosed gap waveguide, the guiding of light can be performed using a transversely closed waveguide structure. For example, a nanocoax similar to the conventional coaxial cable can support near the visible frequency region the plasmon-polariton mode (corresponding to TEM mode for the perfect conductors), which travels in the dielectric medium filled between the inner metallic wire and outer metallic cylinder without a cutoff. Very recently, such a nanocoaxial gap waveguide has been fabricated with the multiwalled carbon nanotube (center conductor with a radius 50 nm), metallic Cr (outer conductor), and the filling medium aluminum oxide (the thickness is 100 nm) [36]. Experimental observations with this subwavelength waveguide have revealed that the propagation length

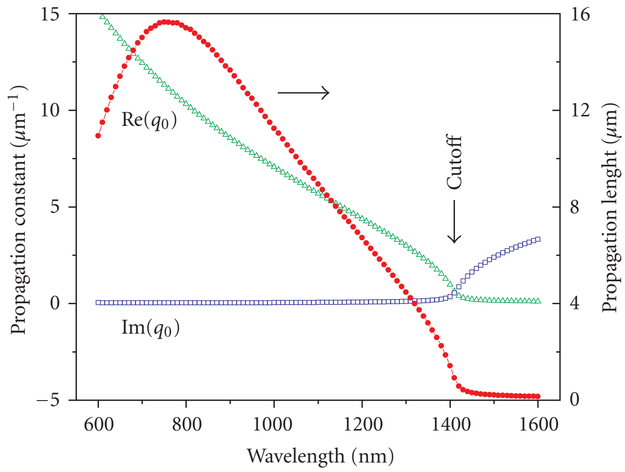


FIGURE 2: Dependence of the propagation constant and energy propagation length of the fundamental waveguide mode on the wavelength. Here, the opening of the square waveguide (silver) is 400 nm∗400 nm, the permittivity of the filling medium is 2.25; Re(q_0) and Im(q_0) represent the real and imaginary parts of the propagation constant, respectively. A maximal propagation length of 15.6 μm can be achieved at the vacuum wavelength 750 nm.

is of many wavelengths of the incident light (the predicted value is up to 50 μm, while 6 μm reported is limited by the fabrication length of the nanocoax). Moreover, rectangular or circular nanoholes similar to the conventional metallic waveguide can also be used to localize and guide the light. To transport the energy more efficiently, the cutoff wavelength of nanohole waveguide can be increased by filling the hole with the dielectric medium. As an example, Figure 2 shows the dependence of propagation constant as well as energy propagation length of a square waveguide on the wavelength ([37, equation (2)] is used here; note that, in the waveguide, the cavity plasmon-polariton mode exists, corresponding to conventional TE_{01} mode). Here, the cross section of a nanohole is assumed to be 400 nm∗400 nm and the permittivity of the filling medium is 2.25 (a thickness of the surrounding silver walls of 100 nm is sufficient for the confinement). It can be seen that the cutoff wavelength is shifted to 1415 nm, below which the propagation of light is allowed, and a maximal energy propagation length up to 15.6 μm can be achieved at the vacuum wavelength 750 nm.

One major factor that hinders the further applications of plasmonic waveguide is the absorption of metal, allowing the propagation length of SPP mode to be finite. It is lucky that such a problem may be surmounted by replacing the passive dielectric with an active gain medium (the permittivity is $\varepsilon_d = \varepsilon_d' + i\varepsilon_d''$ and $\varepsilon_d'' < 0$) [38]. To elucidate this point, we still take the planar metal/dielectric interface as an example. A simple manipulation of (2), assuming that $\varepsilon_m' \gg \varepsilon_m''$ and $\varepsilon_d' \gg -\varepsilon_d''$, yields

$$k_{\mathrm{spp}}'' = \frac{\omega}{2c} \frac{\varepsilon_m'^2 \varepsilon_d'' + \varepsilon_d'^2 \varepsilon_m''}{\sqrt{\varepsilon_m' \varepsilon_d' (\varepsilon_m' + \varepsilon_d')^3}}. \tag{3}$$

Here, k''_{spp} represents the imaginary part of propagation constant of the SPP mode. It can be seen that, when $\varepsilon_m'^2\varepsilon_d'' + \varepsilon_d'^2\varepsilon_m'' = 0$, a lossless propagation of SPP mode can be reached. This corresponds to a gain coefficient $\gamma = -k_0\varepsilon_d''/\varepsilon_d'^{1/2} = k_0\varepsilon_m''\varepsilon_d'^{3/2}/\varepsilon_m'^2$, which is on the order of $1000\,\text{cm}^{-1}$ and can be achieved with the semiconductor-based gain media [38]. Theoretical investigation of gain-assisted SPP propagation has also been extended to metal stripe [38], chains of metal particles [39], and gap waveguide of subwavelength slit [40]. Furthermore, experimental works have been carried out recently, which confirm the existence of the effect [41, 42]. It thus can be expected that plasmonic waveguide combined with appropriate gain medium, owning both subwavelength confinement and (nearly) lossless propagation, could be most promising for the future applications. Further theoretical and experimental works are required.

4. PLASMONIC TRANSMISSION

Besides the light propagation along metal surface, the transmission of light through metal surface is another interesting issue. For a screen, such as a metal film, that is, completely opaque, the presence of a small hole may provide an efficient channel for the light. In classic optics, it is well known that, when the hole size is much larger than wavelength, the light will be diffracted into an Airy pattern with the transmission efficiency close to unity, and when the hole diameter is less than the wavelength, an analytical treatment was found to be difficult. Nevertheless, such a small hole of the subwavelength size is of greater interest due to its fundamental as well as practical importance. In 1928, Synge has proposed a new type of microscope (i.e., near-field microscope) [43], in which a small hole with the diameter ~10 nm milled into an opaque screen is required. When illuminating with the incident light, subwavelength resolution may be achieved under the proper conditions. Moreover, in the current optical data-storage technology, data are recorded by employing a lens to focus laser light onto the optical disk. Due to the diffraction limit, the focus spot is usually of the micrometer scale, which prevents the storage density from being further increased. A possible solution is to use a small hole in an opaque screen instead of a lens to transmit the light [44].

It seems that the above proposal will not work well in practice. Besides the fact that the light will be scattered into all directions when emerging from the small hole, the transmission efficiency was predicted to be extremely low. In 1944, Bethe studied the transmission of light through a single subwavelength hole, assuming that the hole is milled in an infinitely thin and perfectly conducting metal film. At normal incidence, the transmission efficiency for the modeled system is deduced to be [45]

$$t_0 = (64/27\pi^2)(kr)^4. \tag{4}$$

Here, $k = 2\pi/\lambda$ is the free-space wavevector and r is the radius of the hole. Indeed, this transmission efficiency scaling with $(r/\lambda)^4$ is very small and it will be further decreased when considering the finite film thickness. Thus the theoretical result sets up a great barrier for the potential applications.

It is lucky that a favorable turn appeared in 1998 when Ebbesen et al. were studying the optical properties of the perforated metal films [3]. They found that a metal film pierced with subwavelength holes can transmit much more light than one will expect, where the transmission efficiency may be larger than unity when normalized to the area of the holes. This enhanced transmission effect has generated great interest in the scientific community. And since then, much effort has been devoted to the transmission properties of various metallic systems, such as a single hole in a metal film, a single hole surrounded by surface corrugations, as well as metal films with various hole arrays, both theoretically and experimentally [4].

The property of a single hole is important for the study of hole arrays. Recently, a single subwavelength hole in an optically thick and freestanding metal film has been fabricated and tested [46], allowing a comparison to the Bethe's theory. It was found that, for either a circular or a rectangular hole, there is a peak in the transmission spectrum, which is in contrast to the monotonous dependence predicted by (4). The results show that the Bethe's theory is insufficient to describe a real metal system. At least, for a metallic waveguide of finite permittivity and thus increased cutoff wavelength [47], the applicability of the theory should be pushed to $\lambda > \lambda_c$, where λ_c is the cutoff associated with the real rather than perfect metals. To understand the transmission property of a single hole, one should note that, besides the SPP mode excited on the film surface around the hole [12], there is another SPP mode existing in the subwavelength holes [37, 47–49]. This SPP mode called cylindrical surface plasmons or cavity surface plasmons, originating from coupling of light to electrons on the hole walls, is mainly localized in the dielectric core and travels (propagating or evanescent) along the hole axis. Consequently, the cutoff wavelength of the hole is greatly increased and the photons become easier to pass through the subwavelength holes. On the other hand, it has been shown recently that the transmission peak of the subwavelength hole can be attributed to a Fabry-Perot resonance due to multiple reflections of the fundamental cavity mode [50]. And the position of the main resonance was found to be well close to the cutoff wavelength of the waveguide, for both perfect and real metal films [50, 51].

A single subwavelength slit in a metal film makes a great difference to the single hole, where the fundamental slit mode is propagating with no cutoff. Correspondingly, under the illumination of a TM-polarized wave, multiple transmission peaks will be formed when the slit depth is large enough. This Fabry-Perot-like resonance has been predicted theoretically [52], and experimentally confirmed [53]. Compared with the Fabry-Perot resonance condition ($\lambda = 2t/n$, where t is the slit depth and n is an integer), the transmission peaks of the slit exhibit small redshift due to its different boundary conditions. Further experiment suggested that this wavelength shift is related to the permittivity of metal and that the coupled surface plasmons in the subwavelength slit is involved [54].

Here, the attention should be also paid to the slit-groove structure, which has sparked some discussions recently. It was found experimentally that the far-field radiation of a single slit can be modulated by the presence of a groove due to the near-field interactions between them [55]. The transmission efficiency oscillates with the slit-groove distance, where the oscillatory amplitude damps initially with the distance and then maintains a constant. To interpret the above behavior, composite-diffracted-evanescent wave (CDEW) model and SPP mechanism have been employed, respectively. It was turned out that the CDEW model can explain qualitatively the initial damping but fails to predict the constant amplitude [55], whereas the SPP model is just on the contrary [56]. A possible solution is that in the near-zone of groove, many diffraction components are involved, but on the surface, only the SPP mode excited ($k_{//} = k_{spp}$) and a grazing wave ($k_{//} = k_0\sqrt{\varepsilon_d}$) can survive into the far zone. Accordingly, the surface wave originating from the groove and arriving at the slit will interfere with the incident light, leading to the transmission modulation. Similar effect exists in the plasmon-assisted Young's experiment [57]. In contrast to conventional wisdom that the fields at the hole opening are greatly enhanced at the SPP resonance, here, it should be mentioned that the SPP mode will be scattered by the hole, and only a small fraction of SPP can contribute to the light transmission.

The transmission properties of a single subwavelength hole or slit can be further engineered by texturing the metal surface surrounding the hole or slit with periodic corrugations [58–63]. Such a texture can lead to some novel effects in certain wavelength regions, such as the enhanced transmission or beaming of light, depending on which side of the metal film is corrugated. On the one hand, the incoupling of light is associated with the texture on the incident side. When a set of concentric circular (or parallel straight) grooves is added to the input side of the hole (or slit), great enhancement of the light transmission can be obtained [58, 59]. On the other hand, the outcoupling of light is related to the exit side. Correspondingly, when the grooves are made to the output side, highly directional emission from the hole or slit is attainable (the spread angle is only about several degrees) [60, 61]. However, the transmission efficiency (or beam shaping) is not sensitive to the exit (or input) side corrugations. More importantly, when the surface corrugations are fabricated on both sides of the metal film, both collections of incident light and suppression of divergence can be realized efficiently [62, 63]. This high efficiency in coupling in and low divergence in coupling out as well as the small size of the structure, owning the ability to overcome the difficulty aforementioned, have great promise for the applications in, such as subwavelength light sources, near-field optical microscopes, and high-density optical data storage. At present, the physical interpretation of the above phenomena favors a model based on SPP resonance on the textured metal surface [62, 63]. However, further experimental results are not consistent with the SPP model (see [64, Figure 9(b)]). Detailed investigations of the systems revealed that the phenomena are linked to groove cavity mode, light diffraction, and waveguide mode in the slit (or hole) [59, 60], thus possessing a complex physical origin.

In addition, a single subwavelength slit or hole surrounded with surface corrugations can also be used to focus the light [65], where the effect occurs within a narrow frequency range associated with the beaming effect just mentioned. An outstanding property of this subwavelength lens is that the location of the focus is independent on the incident angle. Thus the light impinging from any direction could be focused at the same spot. Moreover, the focus of lens relies on the period and the number of grooves on the exit surface, which can be tailored freely. It is also mentioned that the lens can be constructed with a metal film perorated with subwavelength slits, where the phase retardations of the beams are manipulated by the variant depths or widths of the slits [66, 67].

Now, we come to the subwavelength hole arrays milled in a metal film, which has sparked a renewed interest in surface plasmons that may not be expected initially by Ebbesen et al. [3]. Here, the interest is mainly concentrated on the cases where the film thickness is much larger than the skin depth and the holes do not support the propagating mode. The transmission spectrum of the metal film exhibits a set of maxima and minima, where the peak transmissivity can be orders of magnitude larger than that predicted by Bethe's theory. As an example, Figure 3 presents the measured transmission spectrum (the open circles) of a square hole arrays in a gold film (glass substrate), where the film thickness is 220 nm, the lattice constant is 580 nm, and the hole size is 265 nm∗265 nm. The transmission efficiency for the longer peak around 945 nm is 26%, corresponding to a transmissivity of 1.25. Compared with the 0.145 estimated from (4), this means a ninefold enhancement of the transmission. Similar results have been demonstrated by many experiments [68]. Subsequent contributions have investigated the influence of physical and geometrical parameters on the transmission spectrum, such as the permittivity of the interface media [69], the thickness of the metal film [70], the shape and size of the holes [71–73], the period of hole arrays [74], the symmetry of the lattice [75], the Fourier coefficients of reciprocal vectors [76, 77], and so on. The variation of these parameters will result in a change of the spectrum shape, the peak or dip positions, or the width and height of the peaks, respectively. Moreover, current investigations have been extended from periodic arrays to quasiperiodic, aperiodic, and other structures [77–79], from optical to lower frequencies [78], and from linear to nonlinear regimes [80].

The experimental works are followed by such questions as, how to simulate the measured transmission spectrum, what the underlying physics could be, and what the role of surface plasmons is. The answers to these questions are of both fundamental and practical importance. The first analytical calculation has assumed a square array of square holes, where the predicted peak width is less than 20% of the measured values [81]. The numerical calculation based on a Fourier modal method is very successful, but the deviation of peak position (or width) between theory and experiment is still up to about 80 nm (or 40%) [71]. It is worthy of noticing that, recently, the performance of simulations has been greatly improved, as shown in [49] for circular holes with a numerical method, and [37] for rectangular holes in an analytical way. On the other hand, the mechanism for enhanced transmission has generated many debates [37, 49, 64, 81–87]. Original studies have attributed the transmission minima and maxima to Wood's anomaly and SPP resonance, respectively (note that, for the subwavelength slits, the propagating slit mode plays an important role [88]). At normal incidence, they position, respectively, at [68]

$$\lambda_W = \frac{\sqrt{\varepsilon_d}\, d}{\sqrt{m^2+n^2}}, \qquad \lambda_S = \frac{d}{\sqrt{m^2+n^2}}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m+\varepsilon_d}}. \qquad (5)$$

Here, d is the period of the square lattice, and m and n are two integers associated with reciprocal vectors (which are used for quasiphase matching for SPP resonance). According to this idea, the main dips around 606 nm and 870 nm in Figure 3 should be due to Wood's anomaly at air and glass interfaces, respectively; correspondingly, the main peaks at 710 nm and 945 nm are the result of SPP resonance on either side of the metal film ($m^2 + n^2 = 1$). This seems to be sound but as is in many cases, a quantitative agreement cannot be found [64]. It is also pointed out that the position of the transmission dip is actually dependent on the permittivity of metal (see inset to Figure 3), thus relating the minima to surface plasmons rather than Wood's anomaly.

Compared with a single hole, the hole arrays hold some different characters. For example, the transmission peak of a single hole is close to the cutoff wavelength, but the peak position for hole arrays is larger than, and usually dependent on, the period [89]. This dependence on the period as well as on the hole size suggests that the enhanced transmission benefits from both extended surface modes (diffraction modes) and localized waveguide mode (cylindrical or cavity surface plasmons). The coupling between them can lead to a strong enhancement of fields near the hole opening, which increases the light transmission. As mentioned previously, the surface plasmons in the nanoholes should be commended, which plays a positive role for the guiding of the energy. But the SPP mode in this occasion deserves a further discussion. We stress that, for a single hole, the SPP mode can be locally excited on the surrounding metal surface at any wavelength. But for hole arrays, the strong excitation of SPP mode is possible only when it is resonant with one of the discrete diffraction modes, which is inherent in the periodic metal surface. Analytical formula shows that the SPP resonance is just corresponding to the transmission minimum [37], which agrees with the experiments (also see the shorter arrows in Figure 3). Thus the SPP mode is of a negative effect in the transmission, consistent with the numerical simulations in one-dimensional slits [82]. In other words, the SPP is positive for the reflection of light, as the transmission minimum is related to the reflection maximum [84]. Nevertheless, the proponent of SPP mechanism has suggested that the dispersion relation of SPP mode on the perforated metal surface has been strongly modified, switching the transmission peak to the larger wavelength. Comparing [74] to [86], where the metal surface and the hole inside have been treated either separately or simultaneously, it seems that there is still a question remaining on the horizon: what is the "true" SPP mode? If the dispersion relation of SPP mode has, indeed, been strongly modified, then the position corresponding to the SPP excitation on a flat (unmodulated) metal surface will point at neither the transmission maximum nor the transmission minimum. This is just in contradiction with the theory and experiments. It turns out to be that the SPP mode on a flat metal surface still survives and acts on the perforated metal films.

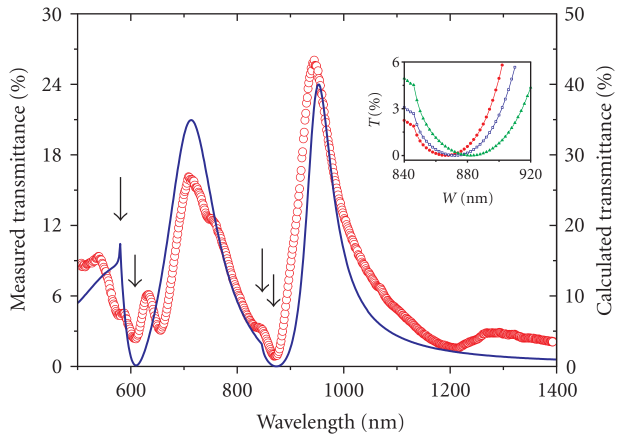


Figure 3: Measured (the open circles) and calculated (the solid line) transmission spectra of gold film perforated with square holes (glass substrate), where the lattice constant is 580 nm, the hole side is 265 nm, and the film thickness is 220 nm. The longer and shorter arrows correspond, respectively, to the Wood's anomaly and SPP resonance. The inset shows the evolution of transmission dip (around 870 nm) with the permittivity of metal (the solid circles, open squares, and solid triangles are calculated with a permittivity of −45, −35, and −25, resp.).

Despite the present and forthcoming discussions on the underlying physics of the phenomena, the proposed structures and effects are of great importance for the future applications. The selective transmission property of the hole arrays enables us to build a filter with the size much smaller than a photonic crystal. When the holes are made to be elliptical, a subwavelength polarizer can be constructed [72]. Moreover, by using the subwavelength hole array masks and enhanced light transmission, high-density nanolithography has been proposed and demonstrated [90]. In addition, the enhanced transmission has also been employed to study the photon entanglement [91, 92], which may be useful for quantum information processing. Again, by varying the electric field (or control light) applied to a liquid crystal (or nonlinear polymer) in contact with hole arrays, switching of the transmission spectrum has been demonstrated [93–96]. This controllable transmission character is very promising for the development of active plasmonic devices. And more recently, the interaction between single fluorescent molecules and isolated single holes in a metal film has been studied by Rigneault et al. [97]. Such investigations show that the molecular fluorescence can be enhanced due to an increase in the local excitation intensity, and that Ebbesen has not forgotten his pursuit for more than ten years [44].

5. THz PLASMONICS

In previous sections, the surface plasmon polariton, plasmonic waveguiding, and transmission have been reviewed focusing on visible and near-infrared frequency. Actually, the SPP mode and the related phenomena also exist in the low-frequency such as THz and microwave range. Recently, increasing interest has been devoted to the THz band (very far infrared) with the development of efficient THz-wave sources [98]. In practice, the THz radiation is very useful for the applications, such as in biology and medicine, as the vibrational modes of many biomolecules just lie in this frequency band. It can be expected that the combination of THz frequency and plasmonic effect will lead to new THz components and boost the development of THz technology. Since the wavelength of THz radiation is very large compared with the visible and infrared light, some special considerations and designs are required.

As we know, for the most metals, the bulk plasma frequency is in the ultraviolet region of the electromagnetic spectrum due to the large free electron density. As a result, the propagating mode or the bulk plasmon polariton are not present in the metal at the THz frequency. One method to overcome this constraint is to use a metamaterial, with the size of the microstructure much smaller than the wavelength. Pendry has proposed, in 1996, a two-dimensional periodic wire structure, which has an effective dielectric response of the Drude-model type when the electric field is polarized along the metallic wire axis [99]. Due to the dilute electron density and self-inductance effect, the plasma frequency is expressed in this case as $\omega_p = \sqrt{2\pi c^2/a^2 \ln(a/r)}$, where c is the speed of light, a is the lattice constant and r is the wire radius. Then the plasmonic response can be engineered by controlling the geometrical parameters of the structure. With this method, a plasma frequency in the THz range (0.7 THz) has been realized using a metallic wire lattice, having the wire diameter of 30 μm, lattice constant of 120 μm and wire length of 1000 μm [100]. The sharp transition of reflection and transmission near the plasma frequency as well as its dependence on the polarization make the structure in the THz optics a high pass filter or a high efficiency polarization filter. Moreover, it has been argued recently that the effective plasma frequency can also be lowered by structuring the metal surface with subwavelength hole arrays [85]. Here the emphasis should be put on a common knowledge that this effective medium response is only valid in the long wavelength limit, which cannot be satisfied in many cases including enhanced light transmission. In addition, based on metallic split-ring resonators as mentioned previously, magnetic response or plasmon polariton has been also realized at the THz frequencies [101]. These plasmonic structures are very important for the construction of THz left-handed medium with both permittivity and permeability to be negative.

In the THz frequency range, the SPP mode on the metal surface is also known as Sommerfeld-Zenneck waves. Due to the lower frequency, the permittivity of metal in this band exhibits a large value (the imaginary part is much larger than the real part). Consequently, for an infinite metal/air interface, the propagation constant given by (2) can be simplified to $k_{\text{spp}} \approx k_0 + ik_0/2\varepsilon_m''$. This means a vanishing wavevector mismatch between the SPP mode and a free-space beam as well as a very long propagation length ($L = \varepsilon_m''/k_0 \sim 10^4$ cm). Moreover, the decay length into air is determined to be $\delta = \sqrt{2\varepsilon_m''}/k_0$, which ($\sim 10$ cm) is much larger than the wavelength, showing a highly delocalized nature of the mode. Recently, with the edge-diffraction coupling near a razor blade [102] or at the corner of a silicon prism [103], the THz SPP mode on a metal surface has been efficiently excited. Nonetheless, the reported propagation length and mode extension are much less than the theoretical values. This discrepancy between theory and experiment may be attributed to the fact that a true Zenneck wave is difficult to establish due to its unique mode features [104]. To confine and guide this delocalized mode, THz waveguide based on various structures has been proposed and demonstrated. Circular and rectangular metal waveguides are useful but with very high group velocity dispersion near the cutoff wavelength [105], which is not beneficial to the propagation of sub-ps THz pulse. Instead, the parallel-plate metal waveguide can transport the TEM mode with a low loss and without a cutoff. With this geometry, a planar THz interconnect layer using quasioptics and broad bandwidth imaging below the diffraction limit have been demonstrated respectively [106, 107]. As an alternative, the coaxial metal waveguide can also support the TEM mode. Compared with the former case, it presents a better mode confinement but with a higher propagation loss [108]. More importantly, it has been shown that the metal wires can be used for THz waveguiding with the advantages of no dispersion, low attenuation, and simple configuration [109]. For a stainless steel waveguide with a diameter of 0.9 mm, an attenuation coefficient as low as 0.03 cm^{-1} has been reported. Moreover, the theoretical calculations suggest that the attenuation coefficient can be further decreased to 0.002 cm^{-1} if the metallic material and wire radius are optimized [110]. Note that such a metal wire waveguide also suffers from a larger-mode profile and significant radiation loss at wire bends [111].

The localization of THz SPP mode can be substantially improved by using a doped semiconductor surface. As we know, semiconductors have a carrier density several orders of magnitude smaller than that of metals, giving rise to a plasma frequency typically in the THz frequency range. Thus semiconductors behave at the THz frequencies as metals in the optical region. Recently, the propagation of THz SPP mode on gratings of grooves structured on a silicon surface has been demonstrated [112]. Due to Bragg reflection, the dispersion and propagation of surface modes are modified. Especially, a stop band is formed in which the in-plane transmission is prohibited. Moreover, the group velocity of the mode is greatly reduced at the edge of bandgap. It is worthy of noticing that the stop band depends strongly on the carrier density of semiconductors, which can be controlled through direct thermal or optical excitation of free carriers. Consequently, the semiconductor permittivity, the in-plane transmission, and the reflection can be artificially modulated [113, 114]. In contrast to this active control using the semiconductors, previous active plasmonics at the optical frequencies has exploited the structural transformation of the waveguide material [115]. On the other hand, similar to the perforated metal films discussed previously, semiconductor surface with subwavelength hole arrays can also support enhanced transmission in the THz frequency range [116]. Moreover, when combined with the thermal or optical excitation, efficient switching of the transmission of THz radiation can be realized [117, 118].

Besides the semiconductor surface, a metal surface structured with corrugations can also be employed to concentrate and guide the THz wave. It has been proposed that, when perforated with subwavelength holes or grooves, a unique electromagnetic surface mode can be supported by a real or even perfect metal surface [85, 119–122]. The dispersion relation of this surface mode is similar to that of a semiconductor grating just mentioned [112] as well as the SPP mode on a flat metal surface. Accordingly, this SPP-like surface mode is also called the designer or spoof surface plasmons. A fascinating property of the SPP-like surface mode is that its dispersion relation is mainly determined by the geometry of the structure. Consequently, the coupling of light to a periodic metal surface and the in-plane transmission can be tailored freely. Recently, the propagation of THz surface mode on a perfect metal surface patterned with square holes of finite depth has been demonstrated theoretically [123]. The results also show that, by varying in lateral directions the hole sizes, efficient THz waveguiding with a two-dimensional confinement can be realized. Furthermore, the theoretical study of THz surface mode has been extended to a perfect metallic wire milled with subwavelength grooves [124, 125]. Although a smooth metal wire can support the THz SPP mode with a low propagation loss, the radial size of the mode is very large as mentioned above. The use of a structured metal wire can easily result in both subwavelength confinement and enhanced THz fields. It is interesting to find that, if the groove depth is gradually increased along the wire, the fields can be increasingly confined to the metal surface [124]. And when a conical structure with a constant groove depth is used, superfocusing of the THz radiation to micron-scale volumes may be achieved. This is an important extension of the nanofocusing with a smooth tapered plasmonic waveguide at the optical frequencies [126]. The results make the proposed structure useful in such applications as THz near-field imaging, spectroscopy, and so on.

To conclude this section, we briefly mention the enhanced transmission of THz radiation through a metal surface with subwavelength holes [78, 127–130]. This has been observed with the periodic, quasiperiodic, and aperiodic hole arrays, and the effect of hole shape and size and the geometrical structure factor on the transmission has been revealed. Compared with the spectrum of optical frequencies, the THz transmission exhibits a larger-transmission coefficient and a much narrower-resonance linewidth [128]. When the perforated metal film is connected to a liquid crystal (or fabricated on a semiconductor substrate), switching of the THz transmission with the magnetic field (or visible light) is possible [129, 130]. In addition, the THz transmission through a single hole surrounded by surface corrugations has been studied recently [131]. This type of structure is also promising for the THz near-field imaging with subwavelength resolutions [132].

6. CONCLUSIONS

Plasmonics possesses rich novel effects that have not been experienced previously. A deep investigation of these effects may provide us with new insight into plasmonics and yield many more future applications. In this paper, we have presented a simple review of this field, putting the emphasis on the plasmonic waveguiding as well as plasmonic transmission and involving both optical and THz frequencies. Although the current understanding of these effects is not complete or even not substantially correct, the materials presented in many literatures are useful and clue us on how to go ahead. Currently, there are many things left to be done [2]. For example, as a key step towards the plasmonic chip, the realization of plasmonic waveguiding with both subwavelength confinement and ultralow propagation loss is still a great challenge. When the gain medium is to be incorporated in the waveguide, an appropriate fabrication method and a pumping scheme should be investigated [40]. For another example, the use of plasmonics in realizing a new type of light sources such as plasmonic nanolaser has been proposed [133, 134]. But the experimental demonstration of the scheme remains to be accomplished. Finally, we express the belief that there is a huge space for us to design new plasmonic structures and excavate novel plasmonic effects. That needs not only well-drilled theoretical basis and experimental skills but also a creative imagination [135].

ACKNOWLEDGMENTS

This work was supported by the State Key Program for Basic Research of China (Grant no. 2004CB619003), and the National Natural Science Foundation of China (Grants nos. 10523001 and 10474042).

REFERENCES

[1] W. L. Barnes, A. Dereux, and T. W. Ebbesen, "Surface plasmon subwavelength optics," *Nature*, vol. 424, no. 6950, pp. 824–830, 2003.

[2] E. Ozbay, "Plasmonics: merging photonics and electronics at nanoscale dimensions," *Science*, vol. 311, no. 5758, pp. 189–193, 2006.

[3] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, "Extraordinary optical transmission through subwavelenght hole arrays," *Nature*, vol. 391, no. 6668, pp. 667–669, 1998.

[4] C. Genet and T. W. Ebbesen, "Light in tiny holes," *Nature*, vol. 445, no. 7123, pp. 39–46, 2007.

[5] S. Nie and S. R. Emory, "Probing single molecules and single nanoparticles by surface-enhanced Raman scattering," *Science*, vol. 275, no. 5303, pp. 1102–1106, 1997.

[6] P. Anger, P. Bharadwaj, and L. Novotny, "Enhancement and quenching of single-molecule fluorescence," *Physical Review Letters*, vol. 96, no. 11, Article ID 113002, 4 pages, 2006.

[7] T. Y. F. Tsang, "Surface-plasmon-enhanced third-harmonic generation in thin silver films," *Optics Letters*, vol. 21, no. 4, pp. 245–247, 1996.

[8] J. Homola, "Present and future of surface plasmon resonance biosensors," *Analytical and Bioanalytical Chemistry*, vol. 377, no. 3, pp. 528–539, 2003.

[9] P. A. Hobson, S. Wedge, J. A. E. Wasey, I. Sage, and W. L. Barnes, "Surface plasmon mediated emission from organic light-emitting diodes," *Advanced Materials*, vol. 14, no. 19, pp. 1393–1396, 2002.

[10] N. Fang, H. Lee, C. Sun, and X. Zhang, "Sub-diffraction-limited optical imaging with a silver superlens," *Science*, vol. 308, no. 5721, pp. 534–537, 2005.

[11] A. V. Zayats, I. I. Smolyaninov, and A. A. Maradudin, "Nano-optics of surface plasmon polaritons," *Physics Reports*, vol. 408, no. 3-4, pp. 131–314, 2005.

[12] L. Yin, V. K. Vlasko-Vlasov, A. Rydh, et al., "Surface plasmons at single nanoholes in Au films," *Applied Physics Letters*, vol. 85, no. 3, pp. 467–469, 2004.

[13] P. Lalanne, J. P. Hugonin, and J. C. Rodier, "Theory of surface plasmon generation at nanoslit apertures," *Physical Review Letters*, vol. 95, no. 26, Article ID 263902, 4 pages, 2005.

[14] B. Hecht, H. Bielefeldt, L. Novotny, Y. Inouye, and D. W. Pohl, "Local excitation, scattering, and interference of surface plasmons," *Physical Review Letters*, vol. 77, no. 9, pp. 1889–1892, 1996.

[15] A. Bouhelier, Th. Huser, H. Tamaru, et al., "Plasmon optics of structured silver films," *Physical Review B*, vol. 63, no. 15, Article ID 155404, 9 pages, 2001.

[16] H. Ditlbacher, J. R. Krenn, N. Felidj, et al., "Fluorescence imaging of surface plasmon fields," *Applied Physics Letters*, vol. 80, no. 3, pp. 404–406, 2002.

[17] H. Ditlbacher, J. R. Krenn, G. Schider, A. Leitner, and F. R. Aussenegg, "Two-dimensional optics with surface plasmon polaritons," *Applied Physics Letters*, vol. 81, no. 10, pp. 1762–1764, 2002.

[18] D. Sarid, "Long-range surface-plasma waves on very thin metal films," *Physical Review Letters*, vol. 47, no. 26, pp. 1927–1930, 1981.

[19] E. Hutter and J. H. Fendler, "Exploitation of localized surface plasmon resonance," *Advanced Materials*, vol. 16, no. 19, pp. 1685–1706, 2004.

[20] S. I. Bozhevolnyi, J. Erland, K. Leosson, P. M. W. Skovgaard, and J. M. Hvan, "Waveguiding in surface plasmon polariton band gap structures," *Physical Review Letters*, vol. 86, no. 14, pp. 3008–3011, 2001.

[21] C. Marquart, S. I. Bozhevolnyi, and K. Leosson, "Near-field imaging of surface plasmon-polariton guiding in band gap structures at telecom wavelengths," *Optics Express*, vol. 13, no. 9, pp. 3303–3309, 2005.

[22] P. Berini, "Plasmon-polariton waves guided by thin lossy metal films of finite width: bound modes of symmetric structures," *Physical Review B*, vol. 61, no. 15, pp. 10484–10503, 2000.

[23] P. Berini, R. Charbonneau, N. Lahoud, and G. Mattiussi, "Characterization of long-range surface-plasmon-polariton waveguides," *Journal of Applied Physics*, vol. 98, no. 4, Article ID 043109, 12 pages, 2005.

[24] P. Berini, "Plasmon-polariton waves guided by thin lossy metal films of finite width: bound modes of asymmetric structures," *Physical Review B*, vol. 63, no. 12, Article ID 125417, 15 pages, 2001.

[25] V. N. Konopsky and E. V. Alieva, "Long-range propagation of plasmon polaritons in a thin metal film on a one-dimensional photonic crystal surface," *Physical Review Letters*, vol. 97, no. 25, Article ID 253904, 4 pages, 2006.

[26] J. R. Krenn, B. Lamprecht, H. Ditlbacher, et al., "Non-diffraction-limited light transport by gold nanowires," *Europhysics Letters*, vol. 60, no. 5, pp. 663–669, 2002.

[27] H. Ditlbacher, A. Hohenau, D. Wagner, et al., "Silver nanowires as surface plasmon resonators," *Physical Review Letters*, vol. 95, no. 25, Article ID 257403, 4 pages, 2005.

[28] K. Leosson, T. Nikolajsen, A. Boltasseva, and S. I. Bozhevolnyi, "Long-range surface plasmon polariton nanowire waveguides for device applications," *Optics Express*, vol. 14, no. 1, pp. 314–319, 2006.

[29] M. Quinten, A. Leitner, J. R. Krenn, and F. R. Aussenegg, "Electromagnetic energy transport via linear chains of silver nanoparticles," *Optics Letters*, vol. 23, no. 17, pp. 1331–1333, 1998.

[30] S. A. Maier, P. G. Kik, H. A. Atwater, et al., "Local detection of electromagnetic energy transport below the diffraction limit in metal nanoparticle plasmon waveguides," *Nature Materials*, vol. 2, no. 4, pp. 229–232, 2003.

[31] S. A. Maier, M. D. Friedman, P. E. Barclay, and O. Painter, "Experimental demonstration of fiber-accessible metal nanoparticle plasmon waveguides for planar energy guiding and sensing," *Applied Physics Letters*, vol. 86, no. 7, Article ID 071103, 3 pages, 2005.

[32] H. Liu, D. A. Genov, D. M. Wu, et al., "Magnetic plasmon propagation along a chain of connected subwavelength resonators at infrared frequencies," *Physical Review Letters*, vol. 97, no. 24, Article ID 243902, 4 pages, 2006.

[33] D. K. Gramotnev and D. F. P. Pile, "Single-mode subwavelength waveguide with channel plasmon-polaritons in triangular grooves on a metal surface," *Applied Physics Letters*, vol. 85, no. 26, pp. 6323–6325, 2004.

[34] S. I. Bozhevolnyi, V. S. Volkov, E. Devaux, and T. W. Ebbesen, "Channel plasmon-polariton guiding by subwavelength metal grooves," *Physical Review Letters*, vol. 95, no. 4, Article ID 046802, 4 pages, 2005.

[35] S. I. Bozhevolnyi, V. S. Volkov, E. Devaux, J.-Y. Laluet, and T. W. Ebbesen, "Channel plasmon subwavelength waveguide components including interferometers and ring resonators," *Nature*, vol. 440, no. 7083, pp. 508–511, 2006.

[36] J. Rybczynski, K. Kempa, A. Herczynski, et al., "Subwavelength waveguide for visible light," *Applied Physics Letters*, vol. 90, no. 2, Article ID 021104, 3 pages, 2007.

[37] C.-P. Huang, Q.-J. Wang, and Y.-Y. Zhu, "Dual effect of surface plasmons in light transmission through perforated metal films," *Physical Review B*, vol. 75, no. 24, Article ID 245421, 7 pages, 2007.

[38] M. P. Nezhad, K. Tetz, and Y. Fainman, "Gain assisted propagation of surface plasmon polaritons on planar metallic waveguides," *Optics Express*, vol. 12, no. 17, pp. 4072–4079, 2004.

[39] D. S. Citrin, "Plasmon-polariton transport in metal-nanoparticle chains embedded in a gain medium," *Optics Letters*, vol. 31, no. 1, pp. 98–100, 2006.

[40] S. A. Maier, "Gain-assisted propagation of electromagnetic energy in subwavelength surface plasmon polariton gap waveguides," *Optics Communications*, vol. 258, no. 2, pp. 295–299, 2006.

[41] J. Seidel, S. Grafström, and L. Eng, "Stimulated emission of surface plasmons at the interface between a silver film and an optically pumped dye solution," *Physical Review Letters*, vol. 94, no. 17, Article ID 177401, 4 pages, 2005.

[42] M. A. Noginov, V. A. Podolskiy, G. Zhu, et al., "Compensation of loss in propagating surface plasmon polariton by gain in adjacent dielectric medium," preprint, 2007 http://arxiv.org/abs/0704.1513.

[43] E. H. Synge, "A suggested method for extending microscopic resolution into the ultra-microscopic region," *Philosophy Magazine*, vol. 6, no. 35, pp. 356–362, 1928.

[44] T. Thio, "A bright future for subwavelength light sources," *American Scientist*, vol. 94, no. 1, pp. 40–47, 2006.

[45] H. A. Bethe, "Theory of diffraction by small holes," *Physical Review*, vol. 66, no. 7-8, pp. 163–182, 1944.

[46] A. Degiron, H. J. Lezec, N. Yamamoto, and T. W. Ebbesen, "Optical transmission properties of a single subwavelength aperture in a real metal," *Optics Communications*, vol. 239, no. 1–3, pp. 61–66, 2004.

[47] R. Gordon and A. G. Brolo, "Increased cut-off wavelength for a subwavelength hole in a real metal," *Optics Express*, vol. 13, no. 6, pp. 1933–1938, 2005.

[48] H. Shin, P. B. Catrysse, and S. Fan, "Effect of the plasmonic dispersion relation on the transmission properties of subwavelength cylindrical holes," *Physical Review B*, vol. 72, no. 8, Article ID 085436, 7 pages, 2005.

[49] N. García and M. Bai, "Theory of transmission of light by subwavelength cylindrical holes in metallic films," *Optics Express*, vol. 14, no. 21, pp. 10028–10042, 2006.

[50] F. J. García-Vidal, E. Moreno, J. A. Porto, and L. Martín-Moreno, "Transmission of light through a single rectangular hole," *Physical Review Letters*, vol. 95, no. 10, pp. 4 pages, 2005.

[51] F. J. García-Vidal, L. Martín-Moreno, E. Moreno, L. K. S. Kumar, and R. Gordon, "Transmission of light through a single rectangular hole in a real metal," *Physical Review B*, vol. 74, no. 15, Article ID 153411, 4 pages, 2006.

[52] Y. Takakura, "Optical resonance in a narrow slit in a thick metallic screen," *Physical Review Letters*, vol. 86, no. 24, pp. 5601–5603, 2001.

[53] F. Yang and J. R. Sambles, "Resonant transmission of microwaves through a narrow metallic slit," *Physical Review Letters*, vol. 89, no. 6, Article ID 063901, 3 pages, 2002.

[54] J. R. Suckling, A. P. Hibbins, M. J. Lockyear, T. W. Preist, J. R. Sambles, and C. R. Lawrence, "Finite conductance governs the resonance transmission of thin metal slits at microwave frequencies," *Physical Review Letters*, vol. 92, no. 14, Article ID 147401, 4 pages, 2004.

[55] G. Gay, O. Alloschery, B. V. de Lesegno, C. O'Dwyer, J. Weiner, and H. J. Lezec, "The optical response of nanostructured surfaces and the composite diffracted evanescent wave model," *Nature Physics*, vol. 2, no. 4, pp. 262–267, 2006.

[56] P. Lalanne and J. P. Hugonin, "Interaction between optical nano-objects at metallo-dielectric interfaces," *Nature Physics*, vol. 2, no. 8, pp. 551–556, 2006.

[57] H. F. Scheuten, N. Kuzmin, G. Dubois, et al., "Plasmon-assisted two-slit transmission: young's experiment revisited," *Physical Review Letters*, vol. 94, no. 5, Article ID 053901, 4 pages, 2005.

[58] T. Thio, K. M. Pellerin, R. A. Linke, H. J. Lezec, and T. W. Ebbesen, "Enhanced light transmission through a single subwavelength aperture," *Optics Letters*, vol. 26, no. 24, pp. 1972–1974, 2001.

[59] F. J. García-Vidal, H. J. Lezec, T. W. Ebbesen, and L. Martín-Moreno, "Multiple paths to enhance optical transmission through a single subwavelength slit," *Physical Review Letters*, vol. 90, no. 21, Article ID 213901, 4 pages, 2003.

[60] L. Martín-Moreno, F. J. García-Vidal, H. J. Lezec, A. Degiron, and T. W. Ebbesen, "Theory of highly directional emission from a single subwavelength aperture surrounded by surface corrugations," *Physical Review Letters*, vol. 90, no. 16, Article ID 167401, 4 pages, 2003.

[61] E. Popov, M. Nevière, A.-L. Fehrembach, and N. Bonod, "Enhanced transmission of light through a circularly structured aperture," *Applied Optics*, vol. 44, no. 32, pp. 6898–6904, 2005.

[62] H. J. Lezec, A. Degiron, E. Devaux, et al., "Beaming light from a subwavelength aperture," *Science*, vol. 297, no. 5582, pp. 820–822, 2002.

[63] A. Degiron and T. W. Ebbesen, "Analysis of the transmission process through single apertures surrounded by periodic corrugations," *Optics Express*, vol. 12, no. 16, pp. 3694–3700, 2004.

[64] H. J. Lezec and T. Thio, "Diffracted evanescent wave model for enhanced and suppressed optical transmission through subwavelength hole arrays," *Optics Express*, vol. 12, no. 16, pp. 3629–3651, 2004.

[65] F. J. García-Vidal, L. Martín-Moreno, H. J. Lezec, and T. W. Ebbesen, "Focusing light with a single subwavelength aperture flanked by surface corrugations," *Applied Physics Letters*, vol. 83, no. 22, pp. 4500–4502, 2003.

[66] Z. Sun and H. K. Kim, "Refractive transmission of light and beam shaping with metallic nano-optic lenses," *Applied Physics Letters*, vol. 85, no. 4, pp. 642–644, 2004.

[67] H. Shi, C. Wang, C. Du, X. Luo, X. Dong, and H. Gao, "Beam manipulating by metallic nano-slits with variant widths," *Optics Express*, vol. 13, no. 18, pp. 6815–6820, 2005.

[68] H. F. Ghaemi, T. Thio, D. E. Grupp, T. W. Ebbesen, and H. J. Lezec, "Surface plasmons enhance optical transmission through subwavelength holes," *Physical Review B*, vol. 58, no. 11, pp. 6779–6782, 1998.

[69] A. Krishnan, T. Thio, T. J. Kim, et al., "Evanescently coupled resonance in surface plasmon enhanced transmission," *Optics Communications*, vol. 200, no. 1–6, pp. 1–7, 2001.

[70] A. Degiron, H. J. Lezec, W. L. Barnes, and T. W. Ebbesen, "Effects of hole depth on enhanced light transmission through subwavelength hole arrays," *Applied Physics Letters*, vol. 81, no. 23, pp. 4327–4329, 2002.

[71] K. J. Klein Koerkamp, S. Enoch, F. B. Segerink, N. F. van Hulst, and L. Kuipers, "Strong influence of hole shape on extraordinary transmission through periodic arrays of subwavelength holes," *Physical Review Letters*, vol. 92, no. 18, Article ID 183901, 4 pages, 2004.

[72] R. Gordon, A. G. Brolo, A. McKinnon, A. Rajora, B. Leathem, and K. L. Kavanagh, "Strong polarization in the optical transmission through elliptical nanohole arrays," *Physical Review Letters*, vol. 92, no. 3, Article ID 037401, 4 pages, 2004.

[73] W. Fan, S. Zhang, B. Minhas, K. J. Malloy, and S. R. J. Brueck, "Enhanced infrared transmission through subwavelength coaxial metallic arrays," *Physical Review Letters*, vol. 94, no. 3, Article ID 033902, 4 pages, 2005.

[74] A. Degiron and T. W. Ebbesen, "The role of localized surface plasmon modes in the enhanced transmission of periodic subwavelength apertures," *Journal of Optics A*, vol. 7, no. 2, pp. S90–S96, 2005.

[75] Q.-J. Wang, J.-Q. Li, C.-P. Huang, C. Zhang, and Y.-Y. Zhu, "Enhanced optical transmission through metal films with rotation-symmetrical hole arrays," *Applied Physics Letters*, vol. 87, no. 9, Article ID 091105, 3 pages, 2005.

[76] Q.-J. Wang, C.-P. Huang, J.-Q. Li, and Y.-Y. Zhu, "Suppression of transmission minima and maxima with structured metal surface," *Applied Physics Letters*, vol. 89, no. 22, Article ID 221121, 3 pages, 2006.
[77] F. Przybilla, C. Genet, and T. W. Ebbesen, "Enhanced transmission through Penrose subwavelength hole arrays," *Applied Physics Letters*, vol. 89, no. 12, Article ID 121115, 3 pages, 2006.
[78] T. Matsui, A. Agrawal, A. Nahata, and Z. V. Vardeny, "Transmission resonances through aperiodic arrays of subwavelength apertures," *Nature*, vol. 446, no. 7135, pp. 517–521, 2007.
[79] J.-Q. Li, W.-Q. Yang, Y.-T. Zhang, Q.-J. Wang, C.-P. Huang, and Y.-Y. Zhu, "Optical transmission through gold film with Archimedean-like subwavelength hole arrays," *Journal of Applied Physics*, vol. 101, no. 7, Article ID 073505, 3 pages, 2007.
[80] J. A. H. van Nieuwstadt, M. Sandtke, R. H. Harmsen, et al., "Strong modification of the nonlinear optical response of metallic subwavelength hole arrays," *Physical Review Letters*, vol. 97, no. 14, Article ID 146102, 4 pages, 2006.
[81] L. Martín-Moreno, F. J. García-Vidal, H. J. Lezec, et al., "Theory of extraordinary optical transmission through subwavelength hole arrays," *Physical Review Letters*, vol. 86, no. 6, pp. 1114–1117, 2001.
[82] Q. Cao and P. Lalanne, "Negative role of surface plasmons in the transmission of metallic gratings with very narrow slits," *Physical Review Letters*, vol. 88, no. 5, Article ID 057403, 4 pages, 2002.
[83] M. M. J. Treacy, "Dynamical diffraction explanation of the anomalous transmission of light through metallic gratings," *Physical Review B*, vol. 66, no. 19, Article ID 195105, 11 pages, 2002.
[84] W. L. Barnes, W. A. Murray, J. Dintinger, E. Devaux, and T. W. Ebbesen, "Surface plasmon polaritons and their role in the enhanced transmission of light through periodic arrays of subwavelength holes in a metal film," *Physical Review Letters*, vol. 92, no. 10, Article ID 107401, 4 pages, 2004.
[85] J. B. Pendry, L. Martín-Moreno, and F. J. García-Vidal, "Mimicking surface plasmons with structured surfaces," *Science*, vol. 305, no. 5685, pp. 847–848, 2004.
[86] P. Lalanne, J. C. Rodier, and J. P. Hugonin, "Surface plasmons of metallic surfaces perforated by nanohole arrays," *Journal of Optics A*, vol. 7, no. 8, pp. 422–426, 2005.
[87] X. Fang, Z. Li, Y. Long, et al., "Surface-plasmon-polariton assisted diffraction in periodic subwavelength holes of metal films with reduced interplane coupling," *Physical Review Letters*, vol. 99, no. 6, Article ID 066805, 4 pages, 2007.
[88] J. A. Porto, F. J. García-Vidal, and J. B. Pendry, "Transmission resonances on metallic gratings with very narrow slits," *Physical Review Letters*, vol. 83, no. 14, pp. 2845–2848, 1999.
[89] C.-P. Huang and Y.-Y. Zhu, "Comment on "Enhanced transmission through periodic arrays of subwavelength holes: the role of localized waveguide resonances""," preprint, 2007, http://arxiv.org/abs/0706.0250.
[90] W. Srituravanich, N. Fang, C. Sun, Q. Luo, and X. Zhang, "Plasmonic nanolithography," *Nano Letters*, vol. 4, no. 6, pp. 1085–1088, 2004.
[91] E. Altewischer, M. P. van Exter, and J. P. Woerdman, "Plasmon-assisted transmission of entangled photons," *Nature*, vol. 418, no. 6895, pp. 304–306, 2002.
[92] S. Fasel, F. Robin, E. Moreno, D. Erni, N. Gisin, and H. Zbinden, "Energy-time entanglement preservation in plasmon-assisted light transmission," *Physical Review Letters*, vol. 94, no. 11, Article ID 110501, 4 pages, 2005.
[93] T. J. Kim, T. Thio, T. W. Ebbesen, D. E. Grupp, and H. J. Lezec, "Control of optical transmission through metals perforated with subwavelength hole arrays," *Optics Letters*, vol. 24, no. 4, pp. 256–258, 1999.
[94] I. I. Smolyaninov, A. V. Zayats, A. Stanishevsky, and C. C. Davis, "Optical control of photon tunneling through an array of nanometer-scale cylindrical channels," *Physical Review B*, vol. 66, no. 20, Article ID 205414, 5 pages, 2002.
[95] G. A. Wurtz, R. Pollard, and A. V. Zayats, "Optical bistability in nonlinear surface-plasmon polaritonic crystals," *Physical Review Letters*, vol. 97, no. 5, Article ID 057402, 4 pages, 2006.
[96] J. Dintinger, I. Robel, P. V. Kamat, C. Genet, and T. W. Ebbesen, "Terahertz all-optical molecule-plasmon modulation," *Advanced Materials*, vol. 18, no. 13, pp. 1645–1648, 2006.
[97] H. Rigneault, J. Capoulade, J. Dintinger, et al., "Enhancement of single-molecule fluorescence detection in subwavelength apertures," *Physical Review Letters*, vol. 95, no. 11, Article ID 117401, 4 pages, 2005.
[98] B. Ferguson and X.-C. Zhang, "Materials for terahertz science and technology," *Nature Materials*, vol. 1, no. 1, pp. 26–33, 2002.
[99] J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs, "Extremely low frequency plasmons in metallic mesostructures," *Physical Review Letters*, vol. 76, no. 25, pp. 4773–4776, 1996.
[100] D. Wu, N. Fang, C. Sun, et al., "Terahertz plasmonic high pass filter," *Applied Physics Letters*, vol. 83, no. 1, pp. 201–203, 2003.
[101] T. J. Yen, W. J. Padilla, N. Fang, et al., "Terahertz magnetic response from artificial materials," *Science*, vol. 303, no. 5663, pp. 1494–1496, 2004.
[102] J. Saxler, J. Gómez Rivas, C. Janke, H. P. M. Pellemans, P. Haring Bolívar, and H. Kurz, "Time-domain measurements of surface plasmon polaritons in the terahertz frequency range," *Physical Review B*, vol. 69, no. 15, Article ID 155427, 4 pages, 2004.
[103] J. O'Hara, R. Averitt, and A. Taylor, "Prism coupling to terahertz surface plasmon polaritons," *Optics Express*, vol. 13, no. 16, pp. 6117–6126, 2005.
[104] T.-I. Jeon and D. Grischkowsky, "THz Zenneck surface wave (THz surface plasmon) propagation on a metal sheet," *Applied Physics Letters*, vol. 88, no. 6, Article ID 061113, 3 pages, 2006.
[105] G. Gallot, S. P. Jamison, R. W. McGowan, and D. Grischkowsky, "Terahertz waveguides," *Journal of the Optical Society of America B*, vol. 17, no. 5, pp. 851–863, 2000.
[106] S. Coleman and D. Grischkowsky, "A THz transverse electromagnetic mode two-dimensional interconnect layer incorporating quasi-optics," *Applied Physics Letters*, vol. 83, no. 18, pp. 3656–3658, 2003.
[107] M. M. Awad and R. A. Cheville, "Transmission terahertz waveguide-based imaging below the diffraction limit," *Applied Physics Letters*, vol. 86, no. 22, Article ID 221107, 3 pages, 2005.
[108] T.-I. Jeon and D. Grischkowsky, "Direct optoelectronic generation and detection of sub-ps-electrical pulses on sub-mm-coaxial transmission lines," *Applied Physics Letters*, vol. 85, no. 25, pp. 6092–6094, 2004.
[109] K. Wang and D. M. Mittleman, "Metal wires for terahertz wave guiding," *Nature*, vol. 432, no. 7015, pp. 376–379, 2004.
[110] Q. Cao and J. Jahns, "Azimuthally polarized surface plasmons as effective terahertz waveguides," *Optics Express*, vol. 13, no. 2, pp. 511–518, 2005.

[111] T.-I. Jeon, J. Zhang, and D. Grischkowsky, "THz Sommerfeld wave propagation on a single metal wire," *Applied Physics Letters*, vol. 86, no. 16, Article ID 161904, 3 pages, 2005.

[112] J. Gómez Rivas, M. Kuttge, P. Haring Bolívar, H. Kurz, and J. A. Sánchez-Gil, "Propagation of surface plasmon polaritons on semiconductor gratings," *Physical Review Letters*, vol. 93, no. 25, Article ID 256804, 4 pages, 2004.

[113] J. Gómez Rivas, M. Kuttge, H. Kurz, P. Haring Bolívar, and J. A. Sánchez-Gil, "Low-frequency active surface plasmon optics on semiconductors," *Applied Physics Letters*, vol. 88, no. 8, Article ID 082106, 3 pages, 2006.

[114] J. Gómez Rivas, J. A. Sánchez-Gil, M. Kuttge, P. Haring Bolívar, and H. Kurz, "Optically switchable mirrors for surface plasmon polaritons propagating on semiconductor surfaces," *Physical Review B*, vol. 74, no. 24, Article ID 245324, 6 pages, 2006.

[115] A. V. Krasavin, A. V. Zayats, and N. I. Zheludev, "Active control of surface plasmon-polariton waves," *Journal of Optics A*, vol. 7, no. 2, pp. S85–S89, 2005.

[116] J. Gómez Rivas, C. Schotsch, P. Haring Bolívar, and H. Kurz, "Enhanced transmission of THz radiation through subwavelength holes," *Physical Review B*, vol. 68, no. 20, Article ID 201306, 4 pages, 2003.

[117] J. Gómez Rivas, P. Haring Bolívar, and H. Kurz, "Thermal switching of the enhanced transmission of terahertz radiation through subwavelength apertures," *Optics Letters*, vol. 29, no. 14, pp. 1680–1682, 2004.

[118] C. Janke, J. Gómez Rivas, P. Haring Bolívar, and H. Kurz, "All-optical switching of the transmission of electromagnetic radiation through subwavelength apertures," *Optics Letters*, vol. 30, no. 18, pp. 2357–2359, 2005.

[119] F. J. García-Vidal, L. Martín-Moreno, and J. B. Pendry, "Surfaces with holes in them: new plasmonic metamaterials," *Journal of Optics A*, vol. 7, no. 2, pp. S97–S101, 2005.

[120] F. J. García de Abajo and J. J. Sáenz, "Electromagnetic surface modes in structured perfect-conductor surfaces," *Physical Review Letters*, vol. 95, no. 23, Article ID 233901, 4 pages, 2005.

[121] M. Qiu, "Photonic band structures for surface waves on structured metal surfaces," *Optics Express*, vol. 13, no. 19, pp. 7583–7588, 2005.

[122] A. P. Hibbins, B. R. Evans, and J. R. Sambles, "Experimental verification of designer surface plasmons," *Science*, vol. 308, no. 5722, pp. 670–672, 2005.

[123] S. A. Maier and S. R. Andrews, "Terahertz pulse propagation using plasmon-polariton-like surface modes on structured conductive surfaces," *Applied Physics Letters*, vol. 88, no. 25, Article ID 251120, 3 pages, 2006.

[124] S. A. Maier, S. R. Andrews, L. Martín-Moreno, and F. J. García-Vidal, "Terahertz surface plasmon-polariton propagation and focusing on periodically corrugated metal wires," *Physical Review Letters*, vol. 97, no. 17, Article ID 176805, 4 pages, 2006.

[125] Y. Chen, Z. Song, Y. Li, et al., "Effective surface plasmon polaritons on the metal wire with arrays of subwavelength grooves," *Optics Express*, vol. 14, no. 26, pp. 13021–13029, 2006.

[126] M. I. Stockman, "Nanofocusing of optical energy in tapered plasmonic waveguides," *Physical Review Letters*, vol. 93, no. 13, Article ID 137404, 4 pages, 2004.

[127] H. Cao and A. Nahata, "Resonantly enhanced transmission of terahertz radiation through a periodic array of subwavelength apertures," *Optics Express*, vol. 12, no. 6, pp. 1004–1010, 2004.

[128] H. Cao and A. Nahata, "Influence of aperture shape on the transmission properties of a periodic array of subwavelength apertures," *Optics Express*, vol. 12, no. 16, pp. 3664–3672, 2004.

[129] C.-L. Pan, C.-F. Hsieh, R.-P. Pan, et al., "Control of enhanced THz transmission through metallic hole arrays using nematic liquid crystal," *Optics Express*, vol. 13, no. 11, pp. 3921–3930, 2005.

[130] E. Hendry, M. J. Lockyear, J. Gómez Rivas, L. Kuipers, and M. Bonn, "Ultrafast optical switching of the THz transmission through metallic subwavelength hole arrays," *Physical Review B*, vol. 75, no. 23, Article ID 235305, 5 pages, 2007.

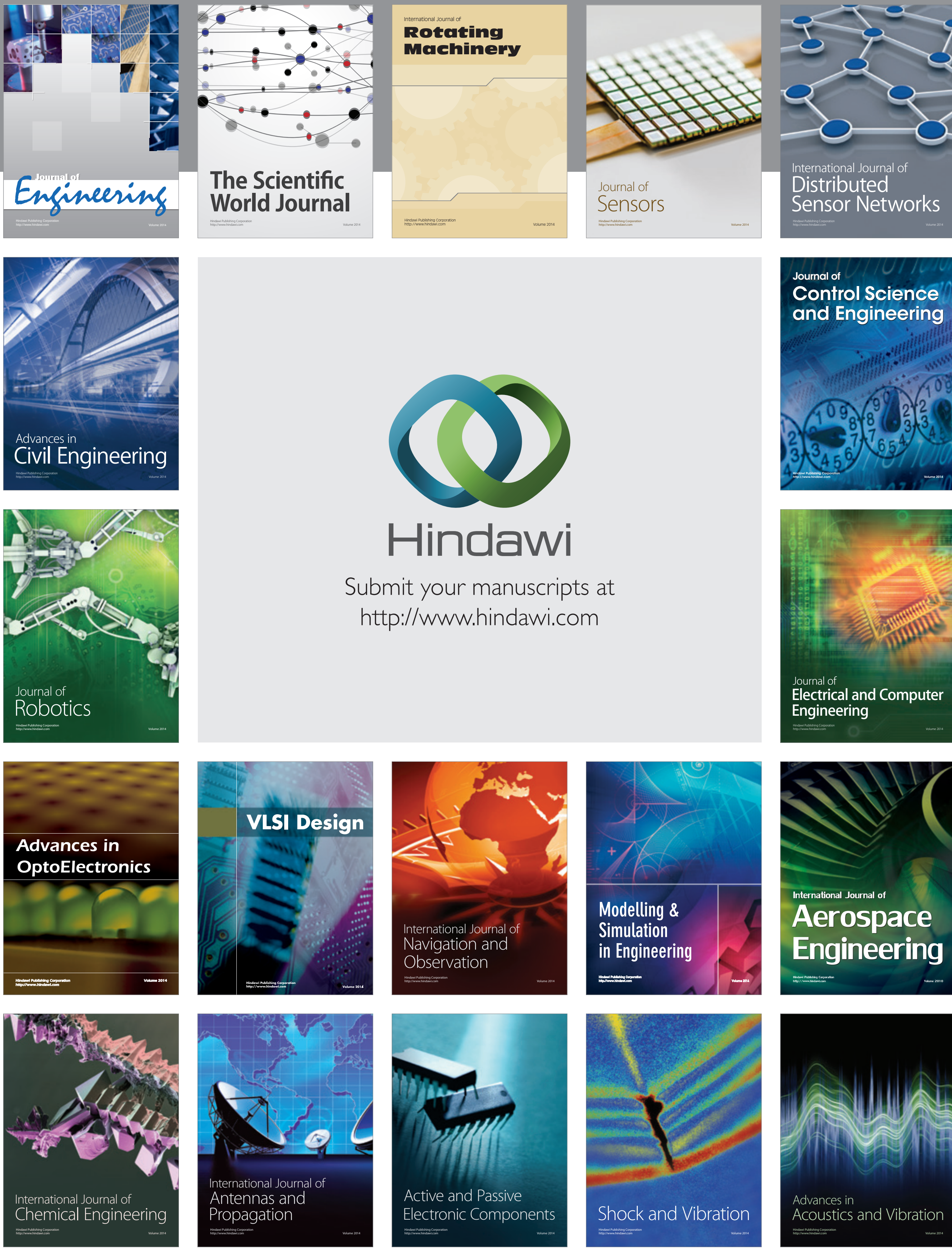
[131] K. Ishihara, G.-I. Hatakoshi, T. Ikari, H. Minamide, H. Ito, and K. Ohashi, "Terahertz wave enhanced transmission through a single subwavelength aperture with periodic surface structures," *Japanese Journal of Applied Physics*, vol. 44, no. 32, pp. L1005–L1007, 2005.

[132] K. Ishihara, K. Ohashi, T. Ikari, et al., "Terahertz-wave near-field imaging with subwavelength resolution using surface-wave-assisted bow-tie aperture," *Applied Physics Letters*, vol. 89, no. 20, Article ID 201120, 3 pages, 2006.

[133] D. J. Bergman and M. I. Stockman, "Surface plasmon amplification by stimulated emission of radiation: quantum generation of coherent surface plasmons in nanosystems," *Physical Review Letters*, vol. 90, no. 2, Article ID 027402, 4 pages, 2003.

[134] A. K. Sarychev and G. Tartakovsky, "Magnetic plasmonic metamaterials in actively pumped host medium and plasmonic nanolaser," *Physical Review B*, vol. 75, no. 8, Article ID 085436, 9 pages, 2007.

[135] J. B. Pendry, D. Schurig, and D. R. Smith, "Controlling electromagnetic fields," *Science*, vol. 312, no. 5781, pp. 1780–1782, 2006.


Journal of Engineering
The Scientific World Journal
International Journal of Rotating Machinery
Journal of Sensors
International Journal of Distributed Sensor Networks
Advances in Civil Engineering
Hindawi
Submit your manuscripts at
http://www.hindawi.com
Journal of Control Science and Engineering
Journal of Robotics
Journal of Electrical and Computer Engineering
Advances in OptoElectronics
VLSI Design
International Journal of Navigation and Observation
Modelling & Simulation in Engineering
International Journal of Aerospace Engineering
International Journal of Chemical Engineering
International Journal of Antennas and Propagation
Active and Passive Electronic Components
Shock and Vibration
Advances in Acoustics and Vibration