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Review Article

Transponder Designs for Harmonic Radar Applications

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This work presents a review on the concept of harmonic or secondary radar, where a tag or transponder is used to respond at a harmonic multiple of the incoming interrogation signal. In harmonic radar, the tag is called a harmonic transponder and the necessary frequency multiplication is implemented using a nonlinear element, such as a Schottky diode. Different applications and operating frequencies of harmonic transponders are presented, along with various tag design aspects. The designer may have to deal with certain tradeoffs during the design with respect to a number of transponder properties, and the role of these tradeoffs is also considered. Additionally, techniques usable for characterization of harmonic transponders are discussed.

1. Introduction

In recent years, the use of different wireless and/or contactless techniques for identifying and tracking various objects has increased significantly. Different technologies that are used range from conventional bar code systems and radio frequency identification (RFID) tags to sensors that potentially allow carrying additional information on the properties and state of an individual object or of the environment. Even though the wireless sensing scheme has become more and more ubiquitous, planned machine-to-machine communication, Internet of Things (IoT), and related technologies bring forward a need for ever increasing wireless sensing [1, 2].

The general concept of wireless sensing involves a sensor and a reader device used to interrogate it. In many implementations, the reader contains both the transmitter (Tx) and receiver (Rx), but in principle they can be separate devices as well. Depending on the sensing scheme, the forward and backward communication from Tx to sensor and from sensor to Rx, respectively, can occur at the same or different frequency bands.

An example of a sensor implementation in which two distinct frequency bands are used for communication is the so-called harmonic or secondary radar, which is one example of nonlinear radar. In the harmonic radar approach, the sensor or tag is called a harmonic transponder. It receives the interrogation signal at a certain fundamental frequency f_0 and converts this signal to a harmonic response signal at frequency nf_0. Here, n is an integer, as the simple frequency multipliers used in the transponders are only able to generate integer multiples. Many of the harmonic transponder designs that are either found in the literature or commercially available are implemented using the second harmonic frequency ($2f_0$), partly due to frequency allocations and because the best transponder conversion efficiency is typically obtained at this frequency [3, 4]. On a conceptual level, harmonic transponders can therefore be described as consisting of a frequency doubler and an antenna [5]. A schematic depiction of the concept is shown in Figure 1.

Harmonic radar is a special case of the more general nonlinear radar concept, in which the response signal is also created through nonlinearities in the transponder. Examples of this can be found in some automotive radar and intermodulation sensor applications, where two closely spaced interrogation signals ($f_1 \approx f_2$) are used instead of a single-frequency signal at f_0. Due to the two signals, the radar response signal occurs at one of the intermodulation frequencies [6, 7]. In some literature, intermodulation-based radar is also referred to as being harmonic.

One of the benefits of using harmonic radar is the possibility to obtain an improved performance in the presence of strong environmental clutter. If the tag would simply respond

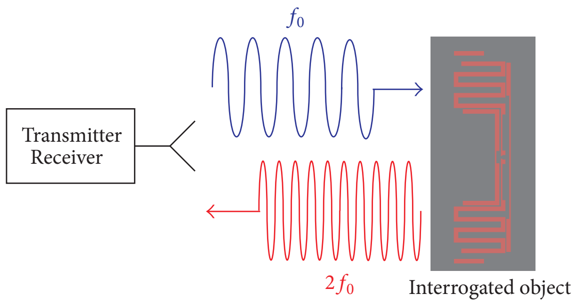

FIGURE 1: Illustration of the harmonic radar concept. Here, the second harmonic frequency $2f_0$ is used for communication.

back at the interrogation frequency in an environment with strong clutter, its response could be obscured by reflections from surrounding objects or by interference from other radio systems operating at the same frequencies. By using a harmonic response signal, it is easier to conclude that the observed response is caused by the tag rather than the surroundings. This is due to the fact that most "natural" objects do not display nonlinear properties at typical power levels used in wireless sensing and therefore are not able to reflect back at other frequencies than the incoming frequency. In the harmonic radar concept, particular attention must be paid to the transmitter power level and nonlinearities, so that the weak received signal can be distinguished from transmitter-based harmonics [8].

This review article provides an overview on different transponder implementations that have been applied in harmonic radar. Section 2 introduces the general design of harmonic transponders along with some important aspects that have to be taken into account during the design process. Various applications in which the harmonic transponder concept has been applied, along with different frequency bands that have been utilized, are presented in Section 3. Examples of actual implementations and of the techniques behind them are shown in Section 4, along with discussion on potential future design techniques. Section 5 provides an insight into techniques used to characterize harmonic transponders. Finally, conclusions are drawn in Section 6.

2. General Design and Requirements of Harmonic Transponders

Primary components of a harmonic transponder are a nonlinear element and an antenna. The nonlinear element can be, for example, a Schottky diode, and it performs the required frequency multiplication from the fundamental frequency to the desired harmonic frequency (typically from f_0 to $2f_0$). Additionally, the nonlinear element should convert the power received by the transponder at f_0 as efficiently as possible to $2f_0$. The antenna takes care of communication between the transponder and Tx/Rx. It should feed as much as possible of the power available at f_0 to the nonlinear element and also radiate the power converted to $2f_0$ as efficiently as possible back to the Rx. In order to obtain this kind of operation, the antenna needs to be matched both at the fundamental and second harmonic frequencies. In addition to matching, the backscattering capability of the transponder depends on its radar cross section (RCS). The effect of different matching conditions and electrical size of the antenna on the RCS of a dipole loaded with a diode is analyzed in [9].

The requirement that the transponder has to operate simultaneously on two different frequency bands (which additionally need to be harmonically spaced) provides a further design challenge. This complicates the transponder design compared to that of regular RFID tags (either single- or dual-band). Antenna designs for conventional RFID tags operating at the UHF range have been previously reviewed in, for example, [10]. The challenge is also in part related to finding a suitable frequency pair that fulfills existing frequency regulations, which has been something of a hindrance for widespread commercial use of harmonic transponders. Considering the impedance level of Schottky diodes often used in the transponders, they typically have a small resistance and large, capacitive reactance. This property is shared by many conventional RFID chips as well.

In some cases, it is desired that the transponder is small in size. The size limitation may pose some challenges regarding the design. A well-known property of designing (electrically) small antennas, for example, for handset applications, is that it is fundamentally impossible to obtain an antenna that would simultaneously have small size, good efficiency, and broad bandwidth. Rather, two out of these three properties or requirements can be met simultaneously. In the case of harmonic transponders, similar constraints are set both by the antenna and the nonlinear element. The impedance characteristics of the diode affect the complexity of the required matching scheme. Increasing the complexity of the matching scheme may necessitate a larger antenna, which can, on the other hand, improve the bandwidth and efficiency properties.

An expression for the power generated by transponder at the second harmonic frequency ($P_{r,2f_0}$) has been formulated in [11, 12], along with figures-of-merit for the transponder antenna and diode used. This expression can roughly be written in the following (slightly simplified) way

$$P_{r,2f_0} \propto \left(1-\Gamma_{f_0}\right)^4 \left(1-\Gamma_{2f_0}\right)^2 \eta_{f_0}^4 \eta_{2f_0}^2 M^2, \qquad (1)$$

where Γ_{f_0} and Γ_{2f_0} relate to the impedance matching at the fundamental and second harmonic frequency, respectively, and M is a term whose value depends on the properties of the particular diode that is used. As can be seen in (1), the properties of the antenna and diode are more important at the fundamental frequency. Additional details on the exact formulation can be found in [11, 12].

The task of the transponder designer is to weigh the different design and performance aspects for the purpose of the targeted application. In some cases, it may be, for example, sensible to allow a slightly worse matching level in order to have a more compact-sized design. Other considerations can also be valid.

Table 1: Summary on the features of some harmonic radar tags found in the literature.

Reference	f_0 & $2f_0$ (GHz)	Transponder dimensions	Mixing element	Type of matching
[11]	1 & 2	$80 \times 35\,\mathrm{mm}^2$ $(l \times w)$	Schottky	Direct
[19]	9.41 & 18.82	$l_{\mathrm{dipole}} = 16\,\mathrm{mm}$, $d_{\mathrm{loop}} = 1\,\mathrm{mm}$	Schottky	Direct
[20]	0.917 & 1.834	$l_{\mathrm{wire}} = 50\,\mathrm{mm}$, $d_{\mathrm{wire}} = 0.152\,\mathrm{mm}$	Schottky	Direct
[29]	1.59 & 3.18	$37.5 \times 11.5\,\mathrm{cm}^2$ $(l \times w)$	Nonspecified diode	Stepped-impedance microstrip lines
[30]	2.45 & 5.9	$l_{\mathrm{dipole}} = 15.7\,\mathrm{cm}$, $w_{\mathrm{dipole,max}} = 1.5\,\mathrm{cm}$	Schottky	Direct
[31]	5.9–6 & 11.8–12	$9.5 \times 9.5\,\mathrm{mm}^2$ $(l \times w)$	Schottky	Direct
[33]	38.5 & 77	$5.15 \times 2.91\,\mathrm{mm}^2$ $(l \times w)$	Schottky	Direct
[41]	0.914 & 1.828	$56 \times 24\,\mathrm{mm}^2$ $(l \times w)$	Schottky	Direct
[42]	2.4 & 4.8	30 mm (diagonal)	Schottky	Impedance transformer based on microstrip lines
[45]	1.3 & 2.6	$44 \times 17\,\mathrm{mm}^2$ $(l \times w)$	Schottky	Direct and external matching

3. Applications and Operating Frequencies

3.1. Transponder Applications. The concept of harmonic radar was first introduced in the 1960s [13], and some of the earliest implementations targeted using it for automotive applications [14, 15]. Harmonic radar has also been applied for studying the steel supports in concrete structures, particularly their corrosion [16]. Here, the use of harmonic radar is based on the inherent nonlinearity of the object under study, and therefore no dedicated transponder is needed. Other example applications of the concept include tracking of insects and small amphibians over distances up to one kilometer [17–25] and locating avalanche victims [26, 27]. In [27], the readout distance of an avalanche detector based on harmonic radar is investigated for different snow thicknesses and also the effect of snow humidity is considered.

Recently, the use of harmonic radar and transponders has been suggested for remote sensing and detection of vital signs in biomedical applications [28], as well as for implementing a quasi-chipless temperature sensor, where the sensor backscattering frequency (at the second harmonic) is temperature dependent [29]. Using nonlinear (harmonic) radar for detecting electronic devices that violate existing emission limits has been contemplated in, for example, [4].

In certain applications, such as insect and amphibian tracking, particular attention has to be paid to the size of the transponder. Obviously, these transponders need to be tracked, but at the same time they have to be sufficiently small and lightweight so as not to prevent the natural movement of the animal. It is also good to keep in mind that, compared to RFID tags that can provide information (or ID) of the object onto which they are attached, typical harmonic transponders do not in most cases enable such a possibility. The transponder mainly provides information on whether it is detected or not; that is, does the receiver pick up a signal at the correct (harmonic) frequency?

3.2. Operating Frequencies. Depending on the targeted application and also in part on existing frequency allocations transponders operating at different frequency bands have been presented. Table 1 summarizes the operating frequencies, transponder dimensions, the type of mixing element used, and the matching scheme of some of the transponders found from the literature. The RECCO avalanche detector of [26] is based on a 0.917 GHz fundamental frequency (whereas the avalanche detector concept of [27] uses a fundamental frequency of 1.25 GHz). Another frequency range that is used is based on maritime radar, using fundamental frequencies around 9.4 GHz [18, 22].

The unlicensed Industrial, Scientific and Medical (ISM) band has also found use in transponder applications and here fundamental frequencies of 2.45, 5.8, or 5.9 GHz have been applied [30–32]. The possibility of using harmonic transponders at millimeter-wave frequencies has also been considered (e.g., 38.5 and 77 GHz in [33]), but the higher path loss at these frequencies restricts the concept to short-range applications compared to various lower-frequency implementations. In [6], an automotive harmonic (intermodulation) radar was suggested using a fundamental frequency in the 76–81 GHz range, and a body-worn harmonic radar tag also operating at automotive radar frequencies around 80 GHz was considered in [34].

4. Transponder Implementations

On a principal level, the required operating frequencies can be obtained by matching the diode directly to the antenna by suitably modifying the antenna geometry or by applying a dedicated matching circuitry. An illustration of the two approaches is shown in Figure 2, where the antenna and matching circuit designs are only indicative.

In the following, different harmonic transponder implementations based on the direct matching scheme presented in the literature are investigated, and the potential, benefits, and drawbacks of using an approach based on separate matching circuits are considered. In both of these approaches, the difference between the impedance characteristics of the antenna and those of the diode (exact impedance level and how steeply it changes as a function of frequency) determines how complex the matching scheme needs to be.

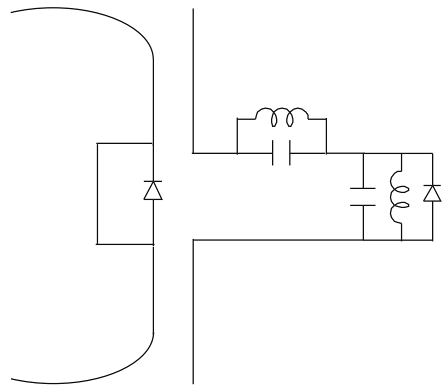

Figure 2: Schematic illustration of the two principal matching techniques applicable to harmonic transponders: (a) direct matching and more complex antenna geometry and (b) external matching circuit and simpler antenna geometry. The figures are only indicative and not to scale.

Considering actual physical implementations, the particular application and intended transponder shape affect to some extent the manufacturing techniques that are suitable. From the literature, different antenna types used in harmonic radar applications range from relatively simple wire antennas (e.g., [19]) to a design that uses a combination of log-periodic dipole antenna and parabolic reflector antenna for implementing harmonic radar operating in the near field [32].

Generally, many of the techniques used to manufacture small antennas can be used, including microstrip technology, but the use of modern or more advanced technologies such as 3D printing has also been suggested. Antennas have been manufactured using 3D printing both for conventional RFID tags [35] and for harmonic radar applications [36]. In both cases, the antenna performance can become sensitive to possible errors in the printing process, such as variance in thickness of the printing material.

4.1. Direct Matching. The first design strategy considered here is to match the diode impedance directly to the load at the desired fundamental and harmonic frequencies (in practice, f_0 and $2f_0$). As can be seen in Table 1, this is a commonly used approach, in which the geometric details of the antenna are modified in such a way that a suitable frequency response is obtained. In a way, the antenna itself becomes a distributed matching network where different geometric details contribute to creating the wanted performance.

Depending on the chosen implementation, the antenna can consist of one or more dedicated parts, each having their own effect on the overall transponder operation. One such design path has been considered in [11, 12, 37], where a transponder consisting of driven and reactive elements is analyzed. Here, the fundamental and second harmonic frequencies are 1 and 2 GHz, respectively, and the transponder along with the obtainable response is illustrated in Figure 3. The frequency pair used in [11, 12, 37] is mainly chosen for demonstrative purposes, and its aim is not to be compliant with any particular frequency allocations.

The antenna shown in Figure 3(a) has dedicated resonant structures for the fundamental and second harmonic frequencies, and the purpose of the reactively loaded elements is to tune the exact resonance frequencies and to improve the coupling level. More details on the design procedure and on the exact effect of the different parts can be found in [37].

Regarding the transponder performance at different frequencies, it was observed in [11] that it is more important to have proper performance at the fundamental frequency than at the second harmonic frequency. This is because the response that the harmonic transponder generates is proportional to the fourth power of transponder properties at f_0 but proportional only to the second power at $2f_0$ (as was seen earlier in (1)).

The performance of harmonic transponders can be characterized and optimized using various analytical, numerical, and empirical techniques. Depending on the requirements of particular implementations, one or more of these approaches may need to be used simultaneously. For instance, in [38, 39], analytical and numerical modeling of a dipole antenna loaded with a diode are considered. On the other hand, the transponder design of [18] is based on empirical modeling. Harmonic transponder characteristics have been analyzed using an equivalent circuit model in [11], and this model is used to obtain the theoretical results in Figure 3(b), which are also compared to measurements performed in an anechoic chamber.

A somewhat similar approach has been considered in [40], where dedicated matching circuits are used to model the fundamental and second harmonic frequencies. The work of [40] provides a comparison of two directly matched antennas for a 5.8 GHz fundamental frequency: a transponder design based on printed circuit boards (PCB) and another one based on a wire dipole. It was observed that, by using the PCB-based approach in connection with a suitable impedance matching technique, it is possible to obtain better sensitivity at low power levels compared to a transponder based on a wire dipole. This observation relates in part to the design tradeoffs discussed in Section 2.

Direct matching based designs have also found many other implementations for harmonic transponders, and some of these are illustrated in Figure 4. For instance, the transponders designed in [19, 20, 30, 31, 41, 42] are based on this technique. The complexity of the implemented antennas varies from simple loop or dipole geometries ([19] and [30], resp.) to a fractal antenna based on a modified Minkowski loop in [31]. A bow-tie antenna is applied in [41], whereas the approach of [42] uses a meandered monopole and a dedicated tuning stub to obtain the desired frequency characteristics.

The design of [20] utilizes a base-loaded monopole antenna, where a loading coil is used to tune the antenna impedance for improved signal strength and also to provide the DC bias required by the Schottky diode used. (In the implementations of [11, 19, 20, 30, 31], the nonlinear element is a Schottky diode.) A DC path is needed because otherwise the buildup of static charge over the diode can damage

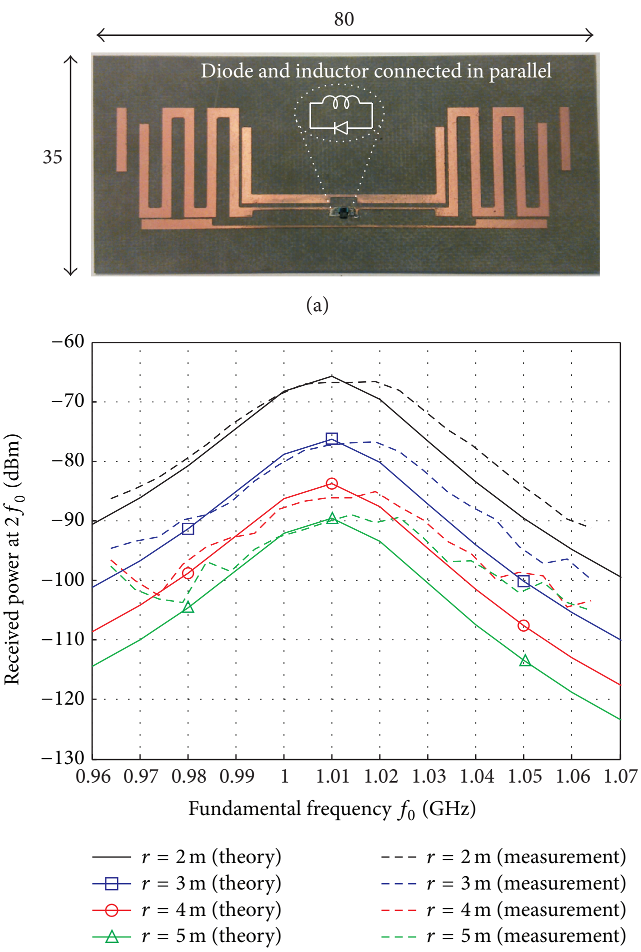

FIGURE 3: (a) Example transponder antenna and (b) obtained theoretical and measured response at the second harmonic frequency $2f_0$, modified from [11].

and also detune it, thereby affecting the performance of the transponder.

4.2. External Matching Circuits. The previously described implementation technique is in principle straightforward, but it can in practice be quite time-consuming. This can be the case, especially if the nonlinear element has a challenging impedance level or if the designer wants to switch to a different diode whose impedance characteristics considerably differ from those of the previously used diode. The effect of using different diodes with a fixed antenna geometry has been investigated in [12]. In that work, it was observed that switching to a different diode may not only shift the operating frequencies but also make the two resonances no longer harmonically separated. The operation of the harmonic transponders is based on having a harmonically separated frequency pair and a lack thereof considerably reduces the obtainable response.

For this reason, one possible alternative is to use a separate, dedicated matching circuit that is responsible for creating the two resonances. The main difference to the previous approach is that the overall performance is considerably less dependent on the properties of the antenna geometry, meaning that the antenna design becomes easier. With a separate matching circuit, the design challenge is partially transferred from an antenna design problem to a circuit design problem, in particular one for finding a sufficiently well-performing circuit topology.

In addition to matching circuits based on discrete, lumped components, it is also possible to consider circuits with distributed components, such as the stepped-impedance microstrip lines in [29] or the microstrip-type impedance transformer matching circuits of [43]. In [43], a harmonic repeater (transponder) was implemented using dedicated antennas for the two operating frequencies. The nonlinear element was matched at the desired frequencies using suitable microstrip line sections of different lengths and impedance levels to transform the complex impedance of the nonlinear element to the 50 Ω level of the antenna element.

As discussed in, for example, [12], the harmonic frequency response can also be implemented using a hybrid approach, in which the properties of both the antenna and separate matching/tuning circuit are used to achieve desired performance. This type of design has been applied in works such as [44, 45]. In [44], meandered shorted patch antennas are used both at the fundamental and second harmonic frequency. The antenna geometries were optimized to tune the impedance characteristics, and additionally matching circuits consisting of lumped and distributed elements were applied. On the other hand, in [45], the antennas used in connection with the matching circuits were quarter-wavelength patch antennas. Both of these cases represent a situation where separate tuning components are used in connection with a resonant antenna, but in a more general case, the antennas can be nonresonant as well.

A key drawback or issue using especially the approach based on lumped components is the potentially high losses caused by the circuit components. This aspect needs to be properly accounted for during the design process. Another matter which has been discussed in the framework of conventional RFID tags is that using separate, surface-mounted components is typically challenging due to issues related to cost and fabrication [46]. However, this approach can prove to be useful in the case of harmonic transponders, especially if the potentially higher losses can at least partially be compensated through reduced overall complexity of the design. This aspect has to be considered with respect to the requirements of an individual application.

4.3. Number of Antennas in the Transponder. In addition to the types of nonlinear element and matching scheme used, it is possible to classify harmonic transponders based on the number of antennas that are implemented. One approach is to use separate antenna elements (and possible matching circuits) at the fundamental and harmonic frequencies, and these are then connected to the nonlinear element. In this case, each antenna element is applied only for one resonance frequency.

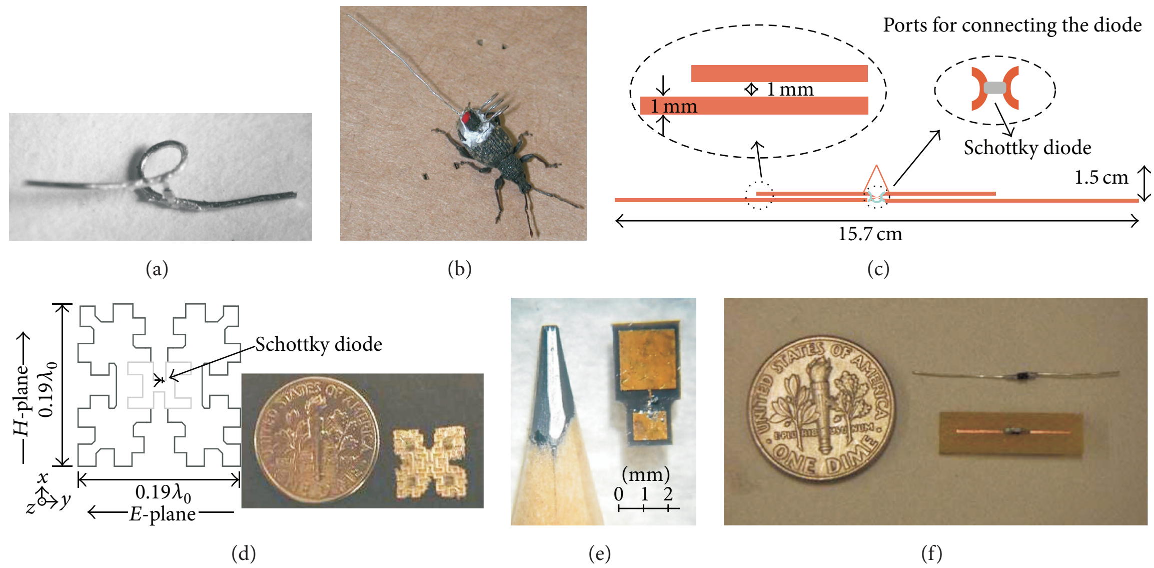

Figure 4: Examples of different transponders found in the literature: (a) dipole with inductive loop [19], (b) monopole with loading coil [20], (c) dipole [30], (d) fractal transponder based on modified Minkowski loop [31], (e) mm wave transponder using patch antennas [33], and (f) dipole on a printed circuit board (PCB) and a regular wire dipole [40]. The different transponder implementations are not to scale, and details on some of these are found in Table 1.

Another possibility is to use a single radiating element to which two different resonances are generated. This can be achieved by using an antenna element having separate resonant paths for different resonant modes or through taking advantage of several resonant modes of a single resonant element for dual-frequency operation [47]. This possibly necessitates the use of a matching circuit.

The number of antennas affects in part the overall complexity of the design. Having more than one antenna typically increases the space occupied by the transponder, but on the other hand this may make the design easier (e.g., through having to match the nonlinear element to the antenna only at one frequency). In some applications, the use of antenna arrays with more than two elements has been suggested ([34, 36, 43]). In [34], a 16-element patch antenna array is used and in [36] two four-element patch antenna arrays are applied (one for transmission and the other for reception). The former approach is more of the nonlinear (intermodulation) kind than strictly harmonic (frequency-doubling), whereas the latter one is intended for true harmonic radar applications.

A slightly different approach is taken in [43], where a transceiver with two pairs of harmonic repeaters operating at slightly different frequencies is used. The first repeater operates using a frequency pair of 2.4 and 4.8 GHz, and it is connected to the sensor element. The other antenna pair acts as a reference at 2.75 and 5.5 GHz (also providing channel calibration and node identification).

5. Harmonic Transponder Characterization

One issue related to improving the design and investigating the performance of harmonic transponders is their characterization. This is due to the fact that the transponder antennas may not necessarily have place for connecting a measurement cable, which can also affect the performance of the device under study. The cable can even begin to act as a significant part of the radiating structure. Furthermore, many conventional measurement techniques are used in a 50 Ω impedance environment, which can be far from the impedance level of the investigated transponder.

Harmonic transponders can be characterized using different techniques, depending in part on the properties that are of interest. The harmonic response of the transponder of Figure 3 (taken from [11]) is obtained by measuring the power reflected from the transponder at $2f_0$. Using the harmonic measurement reveals the frequency that provides the strongest response but does not tell, for example, how well the transponder is matched at the desired frequency bands.

An alternative technique that has been proposed to design, investigate, and characterize both conventional RFID tags and harmonic transponders is based on intermodulation response [48–50]. This approach uses two closely spaced frequencies to illuminate the transponder and measures the intermodulation response generated by transponder nonlinearities. The relation between the intermodulation response and transponder antenna properties has recently been analyzed in detail in [50].

The intermodulation approach enables obtaining valuable information regarding the operation of the transponder, such as radiation pattern and matching level. These can be beneficial both for analyzing the performance of the transponder and for improving it, if necessary. The intermodulation measurement is contactless, which means that the transponder can be measured with the actual load (diode) connected to it, even in the proximity of some object the transponder may be attached to. In the light of current knowledge, this is the best possible approach to characterize harmonic transponders and one that can most accurately replicate real usage conditions.

One aspect related to the different measurement techniques is the amount of equipment needed. Compared to harmonic measurements, the intermodulation-based measurements are more hardware-intensive. This is due to the fact that separate measurement equipment is required for the two closely spaced frequencies, compared to the case of transmitting just one frequency at a time in the harmonic measurements.

During the measurements (both in the harmonic and intermodulation case), it is important to make sure that the wanted, possibly small, response is not suppressed by harmonic or intermodulation responses generated by the measurement equipment itself. This can be obtained, for example, through choosing a suitable equipment placing or measurement geometry. Additional information on these aspects can be found in [50].

6. Conclusion

This paper has presented an overview on harmonic radar and transponders. The concept provides a means of obtaining improved object detection in areas with strong environmental clutter. Different ways of implementing harmonic transponders have been investigated and compared. Transponders of various shapes and sizes can be found from the literature for various frequencies and applications. Harmonic frequency generation is obtained using a nonlinear element, which in most cases is a Schottky diode. Potential techniques for characterizing the properties of harmonic transponders have also been discussed, and their possibilities and limitations are considered.

The future outlook of harmonic transponders seems promising, as new applications for the concept have been proposed in recent years beyond conventional animal tracking and locating of avalanche victims. Most of the implementations that have been presented so far use transponders with an antenna directly matched to the diode. Future and ongoing work in the field includes investigating further alternative design strategies including wider use of transponders with external matching circuits, as well as considering possible novel applications for the harmonic radar concept.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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