Research Article

A Basic Study on RF Characteristics of Meander Line Employing Periodic Ground Structure on GaAs MMIC for Application to Miniaturization of RF Components

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The meander line employing periodic ground structure (MLEPGS) was fabricated on GaAs substrate for application to miniaturization of RF components on MMIC, and its RF characteristics were thoroughly investigated. The MLEPGS with a length of $\lambda/8$ showed loss less than 0.72 dB up to 20 GHz, which was low enough for application to RF passive components. The MLEPGS showed much higher propagation constant β and effective permittivity ϵ_{eff} than conventional meander line. Concretely, the MLEPGS with T of 20 μm showed β of 1.08~20.85 rad/mm and ϵ_{eff} of 2703~2479 from 1 to 20 GHz, while the conventional meander line showed β of 0.18~3.36 rad/mm and ϵ_{eff} of 74.2~64.7 in the same frequency range. According to the result, the size of the $\lambda/4$ transmission line employing the MLEPGS was 0.151 mm², which was 3.5% of the size of the transmission line employing conventional meander line.

1. Introduction

In wireless communication system market, miniaturization of RF passive components has been required constantly for the development of low cost communication system [1–8]. Above all things, transmission line should be miniaturized to reduce the size of RF components, because all distributed RF components basically consist of transmission line. The meander line has been widely used for application to compact transmission line due to its small layout area, which enabled a reduction of chip size [1–5].

For a further reduction of the layout size, we proposed the meander line employing periodic ground structure (MLEPGS) [5, 7]. According to the results, the MLEPGS showed wavelength much shorter than conventional meander line, which enabled realization of highly miniaturized on-chip passive components on MMIC. For application to

various on-chip components on MMIC, basic characteristics of the MLEPGS should be explored thoroughly. We have published several papers dealing with a miniaturized RF component employing the MLEPGS [5, 7]; however, an extensive investigation of basic characteristics on the MLEPGS has not been performed yet.

In this work, using theoretical and experimental analysis, basic characteristics of the MLEPGS were investigated for application to the development of miniaturized on-chip RF passive components. Concretely, for the first time, characteristic impedance was investigated, and periodic capacitance was extracted using theoretical and experimental results to explore basic RF characteristics. In addition, attenuation and propagation characteristics were also investigated for the first time, and effective permittivity was extracted using theoretical and experimental results. Finally, bandwidth characteristic of the MLEPGS was thoroughly investigated for the first time.

FIGURE 1: (a) Measured wavelength of the MLEPGS with various T in a frequency range of 1~10 GHz and (b) 10~20 GHz.

2. Structure of the MLEPGS on MMIC

Recently, our research group has studied the MLEPGS on GaAs substrate [5]. In the MLEPGS, periodic ground structure (PGS) exists between SiN film and GaAs semi-conducting substrate, and it was electrically connected to backside ground plane through the via holes [5, 7]. Therefore, the PGS serves as ground plane with backside ground plane. As is well known, conventional meander line has only a periodical capacitance between line and backside ground plane, while the MLEPGS has additional periodical capacitance due to a coupling between meander line and PGS. Therefore, capacitance of the MLEPGS was much larger than conventional meander line and exhibited wavelength (λ_g) much shorter than conventional meander line, because λ_g is inversely proportional to the periodical capacitance; in other words, $\lambda_g = 1/[f(LC)^{0.5}]$ [5]. The MLEPGS and conventional meander line without PGS were fabricated on GaAs substrate with a height of $100 \mu\text{m}$. For the MLEPGS, the width of PGS pattern T , line width W , and the distance S between lines are all $20 \mu\text{m}$ [5]. For the conventional meander line, line width W and the distance S between lines are all $20 \mu\text{m}$. The total line width W_t for all structure is $140 \mu\text{m}$ [5].

3. Basic RF Characteristic of the MLEPGS on MMIC

3.1. Wavelength and Characteristic Impedance of the MLEPGS. In this work, we compared the wavelengths of the MLEPGS with conventional meander line. The wavelength was defined as the length L of the MLEPGS and conventional meander line with a phase change of 360° . According to our previous study, the MLEPGS showed the wavelength being much shorter than conventional meander line. Concretely, the wavelength of the MLEPGS with T of $20 \mu\text{m}$ was 1.19 mm at 5 GHz , which is 16% of the conventional meander line [5].

FIGURE 2: Characteristic impedance of the MLEPGS according to variation of width of T .

Figure 1 shows the wavelength of the MLEPGS with various widths of PGS, T . As shown in this figure, in a range of T from 5 to $20 \mu\text{m}$, as the value of T increases, wavelength decreases, because an increase of T leads to an increase of capacitance C_b .

We can see that an increase of the T results in an enhancement of periodical shunt capacitance C_b due to an increase of capacitive area. Therefore, the characteristic impedance Z_0 of the MLEPGS can be easily controlled by changing the T , because Z_0 depends on a periodical capacitance of transmission line as shown in

$$Z_0 = \sqrt{\frac{L}{C}}. \quad (1)$$

Dependence of Z_0 on T is shown in Figure 2. Above results indicate that miniaturized RF components with various impedance can be realized by using the MLEPGS.

FIGURE 3: (a) Measured equivalent periodic capacitance of the MLEPGS with T of $20 \mu\text{m}$ and conventional meander line and (b) equivalent periodic capacitance of the MLEPGS with various T .

3.2. Periodic Capacitance of the MLEPGS. As is well known, basic RF parameters of microwave transmission line are expressed by a periodic capacitance and inductance of LC equivalent circuit [9, 10]. Therefore, we extracted the equivalent periodic capacitance from the MLEPGS and the conventional meander line. For a low loss transmission line, the propagation constant β and is given by [10]

$$\beta \approx \omega \sqrt{LC}. \quad (2)$$

Using (1) and (2), we can obtain the following result:

$$C = \frac{L}{Z_0^2} = \frac{\beta}{\omega Z_0} = \frac{1}{\omega Z_0} \cdot \frac{2\pi}{\lambda}. \quad (3)$$

Figures 3(a) and 3(b) show the equivalent periodic capacitance of the MLEPGS and conventional meander line on GaAs substrate. As shown in this figure, the MLEPGS shows capacitance much higher than conventional meander line. Concretely, the MLEPGS with T of $20 \mu\text{m}$ shows the capacitance value of $16.61 \sim 16.76 \text{ pF/mm}$ from 1 to 20 GHz, while the conventional meander line shows the capacitance value of $0.53 \sim 0.55 \text{ pF/mm}$ in the same frequency range. As shown in Figure 3(b), as the value of T increases, periodic capacitance increases, because an increase of T leads to an increase of capacitive area.

3.3. Loss Characteristic of the MLEPGS. In this work, we extracted attenuation constant α from the insertion loss data

using transmission line theory. The electromagnetic wave on transmission line can be expressed as follow:

$$E = E_0 e^{-(\alpha + j\beta)z}, \quad (4a)$$

$$H = H_0 e^{-(\alpha + j\beta)z}, \quad (4b)$$

where α and β are attenuation and propagation constant, respectively. If the electromagnetic wave propagates on a line with a length L , the insertion loss S_{21} can be given by

$$S_{21} \text{ (dB)} = 10 \log |e^{-\alpha L}|^2 |e^{-j\beta L}|^2 = 10 \log |e^{-\alpha L}|^2 \quad (5)$$

$(|e^{-j\beta L}|^2 = 1).$

From the above equation, we can obtain the following attenuation constant:

$$\alpha = \frac{-0.5 \ln [10^{0.1 \times S_{21} \text{ (dB)}}]}{L} \text{ (Np/mm)}. \quad (6)$$

Figure 4 shows measured attenuation constant α of the MLEPGS. As shown in this figure, we can observe the attenuation constant lower than 0.95 dB up to 20 GHz . In this work, we also compared the loss of the MLEPGS with the conventional meander line. For a fair loss comparison, the loss of the MLEPGS and conventional meander line with same electrical length should be compared with each other, because the MLEPGS shows wavelength much shorter than conventional meander line. Therefore, the losses of the MLEPGS and conventional meander line with a length of $\lambda/8$

FIGURE 4: Measured attenuation constant of the MLEPGS.

TABLE 1: Insertion losses of the MLEPGS and conventional meander line with a length of $\lambda/8$.

	Frequency (GHz)			
	5	10	15	20
MLEPGS	0.58 dB	0.72 dB	0.54 dB	0.72 dB
Conventional meander line	0.33 dB	0.31 dB	0.35 dB	0.34 dB

were compared with each other, and the results are shown in Table 1. As shown in this table, the MLEPGS shows loss slightly higher than conventional meander line. Concretely, the loss of the MLEPGS with a length of $\lambda/8$ is less than 0.72 dB up to 20 GHz. In spite of higher loss, the MLEPGS is preferable to the conventional meander, because a size reduction of RF front ends is a key factor for low cost and a little higher loss can be easily compensated by increasing the gain of amplifier.

3.4. Propagation Constant and Effective Permittivity of the MLEPGS. Figure 5 shows propagation constant β of the MLEPGS and conventional meander line on GaAs substrate. As shown in this figure, the MLEPGS shows propagation constant β much higher than conventional meander line. Concretely, the MLEPGS with T of $20 \mu\text{m}$ shows β of $1.08 \sim 20.85 \text{ rad/mm}$ from 1 to 20 GHz, while the conventional meander line shows β of $0.18 \sim 3.36 \text{ rad/mm}$ in the same frequency range. From (2), we can see that the higher periodic capacitance is, the higher β is. Therefore, the higher β of the MLEPGS originates from the higher periodic capacitance of the MLEPGS. As shown in this figure, as the value of T increases, β increases, because an increase of T leads to an increase of periodic capacitance as shown in Figure 3. Above results indicate that a very slow wave exists on the

FIGURE 5: Measured propagation constant of the MLEPGS.

FIGURE 6: Measured effective permittivity of the MLEPGS.

MLEPGS due to its periodic structure, which is favorable for miniaturization of RF components.

Figure 6 shows effective permittivity ϵ_{eff} of the MLEPGS and conventional meander line on GaAs substrate. The ϵ_{eff} was extracted using the following equation:

$$\epsilon_{\text{eff}} = \left(\frac{2\pi}{\omega\lambda} \cdot \frac{1}{\sqrt{\epsilon_0\mu_0}} \right)^2, \quad (7)$$

where ω , λ , ϵ_0 , and μ_0 are angular frequency, wavelength, permittivity, and permeability of air, respectively. As shown in

FIGURE 7: Equivalent circuit of the MLEPGS structure with periodically loaded capacitor C_b .

this figure, the MLEPGS shows much higher effective permittivity than conventional meander. Concretely, the MLEPGS shows ϵ_{eff} of 2,703~2,479 from 1 to 20 GHz, while the conventional meander line shows ϵ_{eff} of 74.2~64.7 in the same frequency range. The higher ϵ_{eff} of the MLEPGS originates from the higher periodic capacitance of the MLEPGS, which can be explained by the following equations. The propagation constant β for nonmagnetic substrate is given by

$$\beta \approx \omega \sqrt{LC} = \omega \sqrt{\mu_0 \epsilon_0 \epsilon_{\text{eff}}}. \quad (8)$$

The above equation leads to the following result:

$$\epsilon_{\text{eff}} = \frac{\sqrt{LC}}{\mu_0 \epsilon_0}. \quad (9)$$

From the above result, we can see that the higher periodic capacitance is, the higher ϵ_{eff} is. As shown in Figure 1, an increase of effective permittivity of the MLEPGS resulted in a reduction of wavelength. As shown in this figure, as the value of T increases, ϵ_{eff} increases, because an increase of T leads to an increase of periodic capacitance as shown in Figure 3.

3.5. Bandwidth Characteristic of the MLEPGS. In this work, bandwidth characteristic of the MLEPGS was thoroughly investigated. The MLEPGS structure can be expressed as the periodically loaded line shown in Figure 7, and C_b is the periodical capacitance between meander line and PGS. Although the MLEPGS has C_a as well as C_b , the periodical capacitance C_a is innately included in the line itself. The periodical susceptance jb is given by

$$jb = \frac{j\omega C_b}{Y_0} = j\omega C_b Z_0, \quad (10)$$

$$b = \omega C_b Z_0.$$

From the structure of MLEPGS, C_b and d can be expressed as follows:

$$d = \frac{S}{2} + W + \frac{S}{2} = S + W,$$

$$C_b = C'_b + C_f,$$

$$C'_b = \epsilon_{\text{SiN}} \cdot \frac{S}{d_{\text{SiN}}} = \epsilon_{\text{SiN}} \cdot \frac{W \times T}{d_{\text{SiN}}}, \quad (11)$$

$$C_f = \epsilon_{\text{SiN}} \cdot \frac{\Delta W \times T}{d_{\text{SiN}}},$$

FIGURE 8: k - β graph of passband and stopband.

where ϵ_{SiN} , d_{SiN} are the permittivity and thickness of the SiN film, and W and S are the width of meander line and spacing between lines. The thickness of the SiN film is 100 nm. In the above equations, we considered the fringing capacitance (C_f) for an accurate calculation, and effective width ΔW for the fringing field was obtained from well-known frequency-dependent equations [10] of meander line, and they were properly modified for application to the MLEPGS structure. The MLEPGS was theoretically characterized using the above equations and a conventional capacitive loaded periodic structure [8]. According to the result, the equations of passband and stopband can be expressed as follow:

$$\cos \beta d = \cos kd - Xkd \sin kd,$$

$$X = \left(\frac{C_b Z_0}{2\sqrt{\epsilon_e} \sqrt{\mu_0 \epsilon_0} d} \right), \quad (12)$$

$$\cos \alpha d = |\cos kd - Xkd \sin kd| \geq 1,$$

where ϵ_e is the effective permittivity of the conventional meander line on GaAs substrate.

Using (12), we can obtain the bandwidth of the passband and stopband from the $\beta d - kd$ graph of Figure 8. In Table 2, the first passband corresponds to practical bandwidth. As shown in Table 2, the bandwidths for the passband and stopband are decreased with an increase of T , which is natural result because an increase of T caused an increase of C_b . As shown in the table, the bandwidth of the MLEPGS is wider than 51 GHz, which means that the MLEPGS can be used as an RF transmission line up to 51 GHz.

4. Conclusions

In this work, the MLEPGS was fabricated on GaAs substrate for application to miniaturization of RF components on MMIC, and its RF characteristics were thoroughly investigated. According to measured results, the MLEPGS exhibited the wavelength much shorter than conventional meander line. Concretely, the wavelength of the MLEPGS with T of 20 μm was 1.19 mm at 5 GHz, which was 16% of the conventional meander line. The characteristic impedance Z_0 of the MLEPGS could be easily controlled by only changing the width of PGS, which indicates that miniaturized RF components with various impedance can be realized by using

TABLE 2: Passband and Stopband of The MLEPGS.

T (μm)	C (pF)	1st passband (GHz)	1st stopband (GHz)	2nd passband (GHz)
5	0.289	$f \leq 78.85$ BW = 78.85	78.85~460.01	460.01~471.69 BW = 11.68
10	0.394	$f \leq 67.18$ BW = 67.18	67.18~460.01	460.01~464.39 BW = 4.38
20	0.668	$f \leq 51.11$ BW = 51.11	51.11~460.01	460.01~464.39 BW = 4.38

the MLEPGS. The MLEPGS with a length of $\lambda/8$ showed loss less than 0.72 dB up to 20 GHz, which was low enough for application to RF passive components. The MLEPGS showed propagation constant β and effective permittivity ϵ_{eff} much higher than conventional meander line. Concretely, the MLEPGS with T of 20 μm showed β of 1.08~20.85 rad/mm and ϵ_{eff} of 2703~2479 from 1 to 20 GHz, while the conventional meander line showed β of 0.18~3.36 rad/mm and ϵ_{eff} of 74.2~64.7 in the same frequency range. The above results indicate that a very slow wave exists on the MLEPGS due to its periodic structure, which is favorable for miniaturization of RF components. In addition, we also extracted the bandwidth of the MLEPGS from the $\beta d - kd$ graph. According to the results, the bandwidth of the MLEPGS is wider than 51 GHz, which means that the MLEPGS can be used as an RF transmission line up to 51 GHz. The above results indicate that the MLEPGS is a promising candidate for application to miniaturization of RF passive components on MMIC up to U band.

Conflict of Interests

The authors of this paper do not have any conflict of interests.

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