Research Article

A Design of a Terahertz Microstrip Bandstop Filter with Defected Ground Structure

Arjun Kumar and M. V. Kartikeyan

Millimeter Wave Laboratory, Department of Electronics and Computer Engineering, Indian Institute of Technology, Roorkee 247 667, India

Correspondence should be addressed to Arjun Kumar; akdec.iitr@gmail.com

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A planar microstrip terahertz (THz) bandstop filter has been proposed with defected ground structure with high insertion loss (S_{21}) in a stopband of -25.8 dB at 1.436 THz. The parameters of the circuit model have been extracted from the EM simulation results. A dielectric substrate of Benzocyclobutene (BCB) is used to realize a compact bandstop filter using modified hexagonal dumbbell-shaped defected ground structure (DB-DGS). In this paper, a defected ground structure topology is used in a $\lambda/4$, $50\ \Omega$ microstrip line at THz frequency range for compactness. No article has been reported on the microstrip line at terahertz frequency regime using DGS topology. The proposed filter can be used for sensing and detection in biomedical instruments in DNA testing. All the simulations/cosimulations are carried out using a full-wave EM simulator CST V.9 Microwave Studio, HFSS V.10, and Agilent Design Suite (ADS).

1. Introduction

THz frequency range spans from 0.1 to 10.0 THz in the electromagnetic spectrum. This THz regime of EM spectrum has been effectively exploited in a variety of applications such as medical spectroscopy, security, space, imaging and measurement of overlaid dielectric substrate [1, 2]. New trends emerging in the development of technology in optical communication systems motivate the requirement of terahertz transmission lines and components [3]. The THz technology is slowly unfolding to mature to meet needs and application specific requirements. Defected ground structures offer compact solutions for the design of microstrip antennas and other passive microwave/millimeter wave components [4]. A lot of literature is available based on defected ground structures for the size reduction of the microstrip filters [4–14]. However, at terahertz frequencies, no considerable work has been reported for the filter design using the defected ground structure (DGS). In this paper, a modified hexagonal dumbbell-shaped DGS/slot in the ground plane is employed in microstrip line at terahertz frequency regime to achieve bandstop characteristics. In this work, a Benzocyclobutene (BCB) substrate is used for the filter design [15].

2. Properties of BCB Dielectric

BCB is a promising organic material which is showing stable permittivity values and low loss over a broad frequency range [15]. The manufacturer [16] claims a dielectric constant $\epsilon_r = 2.65$, with a few percent variations between 10 GHz and 1.5 THz, and the loss tangent of the dielectric BCB is also varying between 0.0008 and 0.002 within the frequency interval from 1 MHz to 10 GHz. Additional data are also available [16] in the frequency range from 400 GHz to 1500 GHz, which confirm a stable dielectric behavior of the BCB on a broad frequency range. However, no specific electrical values are provided in the middle microwave range, below 400 GHz [17].

3. DGS Design Studies of THz Bandstop Filter

Various dumbbell-shaped defected ground structures (DB-DGS) are shown in Figure 1; in this paper, various DB-DGS have been developed on a BCB substrate with height (h) of $11\ \mu\text{m}$ and the permittivity (ϵ_r) of the substrate is 2.6 . There are two reasons for selecting BCB as the substrate [18]. First, it is because that BCB can maintain the value of relative

FIGURE 1: Various configurations of DB-DGS: (a) top view of microstrip line, (b) triangular DB-DGS, (c) square DB-DGS, (d) circular DB-DGS, (e) hexagonal DB-DGS, and (f) modified hexagonal DB-DGS.

FIGURE 2: Comparison of simulated S -parameter of all DB-DGS [22].

permittivity in THz and optical radiation frequency band. Second, the dielectric loss (the part of the insertion loss) of BCB can be considered as zero due to almost zero value of the corresponding loss tangent ($\tan \delta$). In this paper, the dimensions of all the DB-DGS are mentioned in Table 1 with the modified hexagonal DB-DGS with 50 Ω microstrip line having width of 29 μm and thickness of 0.02 μm . Here,

the silver is used for the ground plane and the conducting strip [19].

4. A Comparative Bandstop Characteristics of DB-DGS with the Proposed Modified Design

All the DB-DGS that have been simulated in the CST Microwave Studio EM full-wave simulator are shown in Figure 2. The modified hexagonal indicates a more sharp transition in comparison to all other DB-DGS. It is clear from Table 2 that if the effective capacitance will increase, the sharpness of filter will increase. The 3-dB cut-off frequencies for all the DB-DGS are the same; only the resonant peak will change as per configuration of DB-DGS. In Table 2, the modified hexagonal design has a more effective capacitance in comparison to other DB-DGS. This effective capacitance is responsible for the sharpness of the filter.

The values of effective inductance and effective capacitance are calculated by the circuit extraction techniques using the following formulas [5–7]:

$$C = \frac{5f_c}{\pi [f_o^2 - f_c^2]} pf, \quad (1)$$

$$L = \frac{250}{C(\pi f_o)^2} nH, \quad (2)$$

$$\text{Sharpness factor} = \frac{f_c}{f_o}. \quad (3)$$

FIGURE 3: (a) L - C equivalent circuit model; (b) S -parameter characteristics by co-simulation in ADS [23].

5. Calculation of Various Losses for the Proposed Design DB-DGS

As the frequency increases, the losses also increase. Here, in this paper, various losses are calculated for studying the behavior of microstrip terahertz filter using a BCB substrate with height (h) = 11 μm , permittivity (ϵ_r) = 2.6, width of the silver metal strip conductor (W) = 29 μm , thickness of strip (t) = 0.02 μm , and length of the conducting strip (L) = 50 μm . These losses are conductor loss, dielectric loss, and radiation loss which are calculated by using the formulas, given below.

Conductor Loss (see [20]). For the proposed DB-DGS in Figure 1(f), the conductor loss is 100 (nepers/meter) or 20 dB/meter. This is conductor loss is calculated by using (4) to (7) [20]:

$$\alpha_c = \frac{R'}{2 \cdot Z_o}, \quad (4)$$

$$R' = \frac{R_{sh}}{W}, \quad (5)$$

$$R_{sh} = \frac{\rho}{\delta}, \quad (6)$$

$$\delta = \sqrt{\frac{2\rho}{2\pi f \mu_0 \mu_r}}, \quad (7)$$

where α_c is conductor loss, R' is the resistance of entire strip, R_{sh} is sheet resistance of silver metal conductor, W is the width of the silver metal conductor, Z_o is characteristic impedance of line, δ is skin depth, and ρ is resistivity of metal.

Dielectric Loss and Loss Tangent (see [15, 21]). The attenuation α at 1.4 THz is calculated directly that is -25.8 dB from the simulated S -parameter and α_c is calculated from (4) for silver

metal. For the BCB at 1.4 THz, the dielectric loss is 5.8 dB and the loss tangent is 0.0002 which is calculated by using (8)

$$\begin{aligned} \alpha_d &= \alpha - \alpha_c, \\ \tan \delta &= \frac{\lambda_o}{\pi} \cdot \frac{\alpha_d \sqrt{\epsilon_{eff}}}{\epsilon_r} \cdot \frac{\epsilon_r - 1}{\epsilon_{eff} - 1}, \\ \epsilon_{eff} &= \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 10 \frac{h}{W} \right]^{-0.5}. \end{aligned} \quad (8)$$

Here, α_d is dielectric loss, $\tan \delta$ is loss tangent, ϵ_r is relative permittivity, ϵ_{eff} is effective permittivity, and h is height of the substrate.

Radiation Loss at 1.4 THz (see [8]). The radiation loss is calculated using simulated S -parameter of the proposed DB-DGS that is shown in Figure 1(f). The area of the proposed filter is 87 $\times$ 50 μm^2 . Consider

$$\eta = 1 - |S_{11}|^2 - |S_{21}|^2. \quad (9)$$

Here, at 1.4 THz, the radiation loss is 0.22 or -6.5 dB.

6. L - C Modelling and Cosimulation of Proposed DB-DGS

The L - C parallel resonator circuit has been designed for the modified defect in the ground plane by the circuit extraction techniques [20]. The extracted value of inductance (L) is 8.20×10^{-3} nH and the capacitance (C) is 1.50×10^{-3} pF calculated by the formulas given in (1)-(2) which have been shown in Table 2. This L - C model is cosimulated in ADS2006A. The simulated results are shown in Figure 3 which are in good agreement with the simulated results in CST MW Studio in Figure 4 for the modified hexagonal DB-DGS.

7. Results and Discussion

The extracted value of inductor and the capacitance of the simulation S -parameter results, the equivalent circuit model

TABLE 1: Dimensions of various design configurations.

S. no.	Design configuration of DB-DGS	a (μm)	g (μm)	d (μm)	r or r' (μm)	r'' (μm)	k (μm)
1	Circular	—	2	12	4.6	—	—
2	Hexagonal	—	2	12	3.1	—	—
3	Triangular	13.1	2	12	—	—	—
4	Square	8.2	2	11	—	—	—
5	Modified hexagonal DGS	—	2	11	5.2	2.6	1.7

TABLE 2: Dimensions of various design configurations.

S. no.	Design configuration of DB-DGS	$f_c = 3\text{-dB}$ cut-off (GHz)	f_o resonant frequency (GHz)	Inductance (L) in nH	Capacitance (C) in pF	Sharpness factor
1	Circular	1000	1458.6	8.43×10^{-3}	1.41×10^{-3}	0.66
2	Hexagonal	1000	1447.9	8.34×10^{-3}	1.45×10^{-3}	0.7
3	Triangular	1000	1446.1	8.30×10^{-3}	1.46×10^{-3}	0.71
4	Square	1000	1448.8	8.33×10^{-3}	1.44×10^{-3}	0.72
5	Modified Hexagonal	1000	1436.2	8.20×10^{-3}	1.50×10^{-3}	0.77

FIGURE 4: Simulated S -parameter of modified hexagonal DB-DGS [22].

of DGS is designed in ADS and again it is simulated; the simulated results of this equivalent circuit show better agreement between the simulation results of S -parameters of proposed design as shown in Figure 4; in both cases, the results are almost same. In both the CST Microwave Studio V9 and Agilent ADS2006A, the simulated results show the same cut-off frequency which is approximately 1.000 THz. At this cut-off frequency, the size of filter is in μm , so the size of the proposed filter is very small and the total area of this filter is $87 \times 50 \mu\text{m}^2$. The various losses have been calculated as insertion loss (S_{21}) in stopband -25.8 dB, dielectric loss is 5.8 dB, conductor loss or attenuation is 20 dB/meter, and radiation loss is 0.22 .

In Figure 5, the proposed modified hexagonal DB-DGS bandstop filter is cosimulated in various electromagnetic

FIGURE 5: Comparison of the proposed modified DB-DGS bandstop filter in various EM simulated tools.

(EM) simulation tools for the verification and validation of the proposed filter. In all the cases, the cut-off frequency and resonant frequencies are almost the same. In case of HFSS simulation, the S -parameter is a little bit distorted. But in all the way, all results in EM simulation tools are in good agreement. For the simulation of proposed filter, absorbing boundary condition has been used to reduce the radiation effect.

8. Conclusions

Many researchers are working on THz filter, but no work is reported on filter design on THz frequency with DGS

using microstrip. An approach is developed in this paper, and a microstrip bandstop filter has been designed at the cut-off frequency of 1.000 THz with the insertion loss of -25.8 dB at 1.4 THz in a stopband; no stub or stepped-impedance structure is used. Only 50 ohm $\lambda/4$ microstrip line with modified hexagonal-shaped DGS shows the bandstop characteristics at 1.000 THz. The simulated *S-parameter* is in excellent agreement with the calculated one, especially in reflection coefficient and insertion loss in both simulator CST Microwave Studio V9 and ADS200A. All the basic DB-DGS have been studied for terahertz frequency and their sharpness is compared which is shown in Table 2. The modified DB-DGS is sharper than the other DB-DGS. In the literature, so far no fabrication has been reported on microstrip filter at terahertz frequency. For the validation, the proposed filter is simulated in various EM wave simulators like CST, HFSS, and ADS. After comparison of all simulated results, it was found that the results are in good agreement.

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