Characterization of Thin Film Coupled Microstrip Line for Terahertz Frequency - Range

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Abstract: ***The dispersion characteristics and loss analysis of coupled microstrip line on low loss thin film cyclic-olefin copolymer dielectric substrate are investigated in this paper. The even-mode and odd-mode capacitances are computed using closed-form expressions derived from conformal mapping method. The frequency dependent parameter- impedance, effective relative permittivity, dielectric loss and conductor loss for even-mode and odd-mode are computed to analyze the coupled microstrip line.***

Keywords: Thin film Coupled Microstrip Line, Dielectric Loss, Conductor Loss.

1. Introduction

In the last decade, due to complexity and miniaturization of components in the microwave integrated circuits (MICs), the connecting transmission lines and components are designed on thin film dielectric substrates. Owing to effective transmission and low loss features, the thin film transmission lines show huge potential in high-speed communications and component design. Planar transmission lines - microstrip line and coplanar waveguides are employed in the design of microwave integrated circuits (MICs) and monolithic MICs [1-5].

In this work, theoretical analysis of basic characteristics of coupled microstrip line on thin film dielectric substrate are presented. In coupled microstrip line, two microstrip lines are kept close to each other. The coupled microstrip line are excited in even-mode and odd-mode. Conformal mapping based closed-form expressions are used to compute even-mode and odd-mode capacitance of edge-coupled microstrip line. The even-mode and odd-mode effective relative permittivity and impedance are computed from even-mode and odd-mode capacitances. The dispersion characteristics for effective relative permittivity and impedance are calculated from Kirschning and Jansen dispersion relation. The dielectric loss and conductor loss are obtained for even-mode and odd-mode using transmission line lumped parameters. The electromagnetic coupling between two microstrip lines can be used to design directional couplers. Due to low dispersion, the directional can be designed in broad frequency band [1, 6-11]. The formulation to determine the even-mode and odd-mode capacitances of coupled microstrip line, impedance, effective relative permittivity and loss characteristics are present in section-II. The calculated numerical results are presented in section-III.

2. Analysis of Edge-Coupled Microstrip Line

The structural cross-section view of a coupled microstrip line is shown in Fig.1. The width of microstrip line is S. The gap between coupled microstrip line is 'G'. The thickness and permittivity of dielectric substrate are H and ε_r respectively. The capacitances for edge-coupled microstrip line are used to compute the static impedance and effective relative permittivity. The even-mode and odd-mode capacitances are calculated from the following equations.

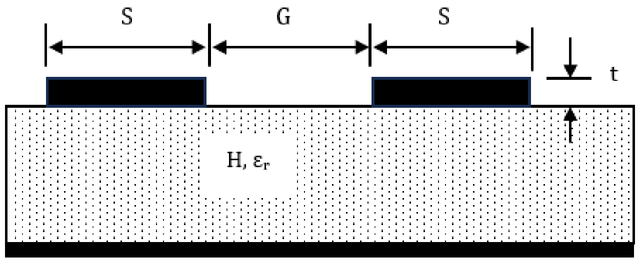

Figure 1: Coupled Microstrip Line

$$C_e = 2\varepsilon_o\left[\varepsilon_r\frac{K(k_1)}{K(k_1')} + \frac{K(k_2)}{K(k_2')}\right] \quad (1a)$$

$$C_o = 2\varepsilon_o\left[\varepsilon_r\frac{K(k_3)}{K(k_3')} + \frac{K(k_4)}{K(k_4')}\right] \quad (1b)$$

$$k_1 = tanh\left(\frac{\pi S}{4H}\right) tanh\left[\frac{\pi(S+G)}{4H}\right] \quad (1c)$$

$$k_2 = tanh\left[\frac{\pi S}{4(H+\pi S)}\right] tanh\left[\frac{\pi(S+G)}{4(H+\pi S)}\right] \quad (1d)$$

$$k_3 = tanh\left[\frac{\pi S}{4H}\right] coth\left[\frac{\pi(S+G)}{4H}\right] \quad (1e)$$

$$k_4 = \frac{S}{S+G} \quad (1f)$$

$$k_1' = \sqrt{1-k_1^2} \quad (1g)$$

$$k_2' = \sqrt{1-k_2^2} \quad (1h)$$

$$k_3' = \sqrt{1-k_3^2} \quad (1i)$$

$$k_4' = \sqrt{1-k_4^2} \quad (1j)$$

Where K(k) is complete elliptic integral of first kind. Equation (1) leads to the following results for even-mode and odd-mode effective relative permittivity.

$$\varepsilon_{reff\,e}(f=0) = \frac{C_{e\,diel}}{C_{e\,air}} \quad (2a)$$

$$\varepsilon_{reff\,o}(f=0) = \frac{C_{o\,diel}}{C_{o\,air}} \quad (2b)$$

Following Kirschning and Jansen dispersion model for microstrip line gives frequency dependent effective relative permittivity.

$$\varepsilon_{reff\ e,o}(f) = \varepsilon_r - \frac{\varepsilon_r - \varepsilon_{reff\ e,o}(f=0)}{1+B(f)} \quad (3a)$$

$$B(f) = B_1 B_2 [(0.1844 + B_3 B A_4) f_H]^{1.5763} \quad (3b)$$

$$B_1 = 0.27488\left[0.6315 + \frac{0.525}{(1+0.0157 f_H)^{20}}\right]\frac{S}{H} - \left[0.065683 exp\left(-8.7513\frac{S}{H}\right)\right] \quad 3(c)$$

$$B_2 = 0.33622[1 - exp(-0.03442\varepsilon_r)] \quad (3d)$$

$$B_3 = 0.0363\left[exp\left(-4.6\frac{S}{H}\right)\right]\left[1.0 - exp\left[-\left(\frac{f_H}{38.7}\right)^{4.97}\right]\right] \quad (3e)$$

$$B_4 = 1 + 2.751\left[1.0 - exp\left[-\left(\frac{\varepsilon_r}{15.916}\right)^{8}\right]\right] \quad (3f)$$

$$f_H = f.H = normalized\ frequency\ in\ [GHz.mm], \quad 1 \le \frac{S}{H} \le 100\ and\ 1 \le \varepsilon_r \le 20 \quad (3g)$$

The impedance can be determined from following relation

$$Z_{eff\ e,o}(f) = \frac{Z_o(f=0)}{\sqrt{\varepsilon_{reff\ e,o}(f)}} \quad (4)$$

The dielectric loss due to finite conductivity of dielectric substrate is computed from distributed conductance (G) given in [1].

$$\alpha_{d\ e,o} = \frac{G\ Z_{eff\ e,o}(f)}{2} \quad (5a)$$

$$G = \omega\varepsilon_o\varepsilon_r tan\delta\left[\left(\frac{S}{H}\right)^{1.08} + \left[\pi\left(\frac{1}{log\left(\frac{8H}{S}+1\right)} - \frac{S}{8H}\right)\right]^{1.08}\right]^{1/1.08} \quad (5b)$$

The conductor loss in microstrip line with thickness 't' is given in by-

$$\alpha_{c\ e,o} = \frac{R_{dc}+R_{ac}}{2\ Z_{eff\ e,o}(f)} \quad (6a)$$

The direct-current (dc) resistance (R_{dc}) and alternating-current (ac) resistance (R_{ac}) are obtained from conductivity (σ) and cross-sectional dimension of microstrip line given in [1].

$$R_{dc} = \frac{1}{\sigma S t}, \qquad R_{ac} = \frac{1}{\sigma\delta(S+t)} \quad (6b)$$

$$\text{skin depth } (\delta) = \sqrt{\frac{2}{\omega\sigma\mu_o\mu_r}} \quad (6c)$$

3. Numerical Results and Discussion

The coupled microstrip line on thin film cyclic-olefin copolymer (COC) dielectric substrate is considered for analysis. The coupled microstrip line is designed for 10dB coupling. The relative permittivity and loss tangent of COC dielectric substrate are 2.35 and 0.0005 respectively. The thickness of COC dielectric substrate is H=20μm. For 10dB coupling, H=20μm and W=20μm and gap (G) is 8.7μm. Similarly for H=20μm and W=30μm the gap (G) is 7.1μm. The even-mode and odd-mode impedance, effective relative permittivity, dielectric loss and conductor loss are calculated for two different cases i.e., W=20μm, G=8.7μm and W=30μm, G=7.1μm. The frequency dependent even-mode and odd-mode impedance, effective relative permittivity, dielectric loss, conductor loss and coupling are shown in Fig. 2(a)-2(e) and Fig. 3(a)-3(e).

Fig. 2(a) and Fig. 2(b) show the even-mode and odd-mode impedance for H=20μm, W=20μm, G=8.7μm. The even-mode and odd-mode impedances at 100GHz are 116.44 ohm and 60.46 ohm respectively. At 1THz, the even-mode and odd-mode impedances are 114.66 ohm and 58.84 ohm respectively. The effective relative permittivity for even-mode and odd-mode at 100GHz are 1.963 and 1.738 respectively. At 1THz these values are 2.024 and 1.835. The variation in impedance and effective relative permittivity are very small in frequency range from 100GHz to 1THz. It clearly shows that microstrip coupled line can be used to design broadband coupler in this frequency range. Fig. 2(c) and Fig. 2(d) show the dielectric loss and conductor loss for coupled microstrip line. The even-mode and odd-mode dielectric loss at 100GHz are 0.00671dB/mm and 0.00348dB/mm. The even-mode dielectric loss is more than odd-mode. The even-mode and odd-mode dielectric loss at 1Thz are 0.066dB/mm and 0.0339dB/mm respectively. The conductor loss for even-mode and odd-mode are 0.168dB/mm and 0.324dB/mm at 100GHz. The conductor loss for odd-mode is more than even-mode. The dielectric loss is less than conductor loss due to small loss tangent of dielectric substrate. Both even-mode and odd-mode dielectric loss and conductor loss increase with frequency. Fig. 2(e) shows the coupling in the frequency range from 100GHz to 1THz. The variation in coupling is very small in this range. Fig. 3(a)-3(d) show impedance, effective relative permittivity, dielectric loss and conductor loss for another set of strip width W=30μm, G=7.1μm and 10dB coupling. As the microstrip line width increases from 20μm to 30μm, the even-mode and odd-mode impedance decreases and effective relative permittivity increases. The variation of impedance and effective relative permittivity is also very small in this frequency range. Dielectric loss increases and conductor loss decreases with increase of strip width. Fig. 3(e) shows the coupling in the frequency from 100GHz to 1THz. Broadband microstrip line coupler can be designed in this frequency range.

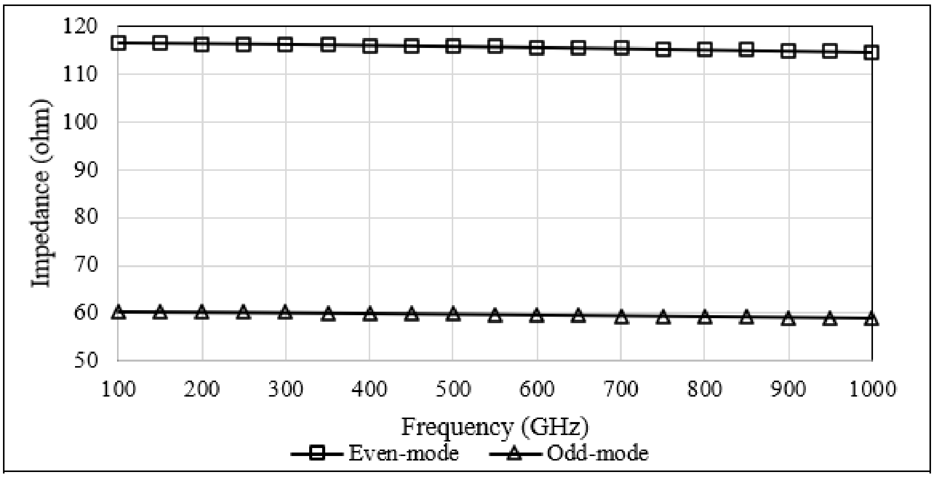

Figure 2 (a): Impedance Zo (ohm), W=20µm, G=8.7µm.

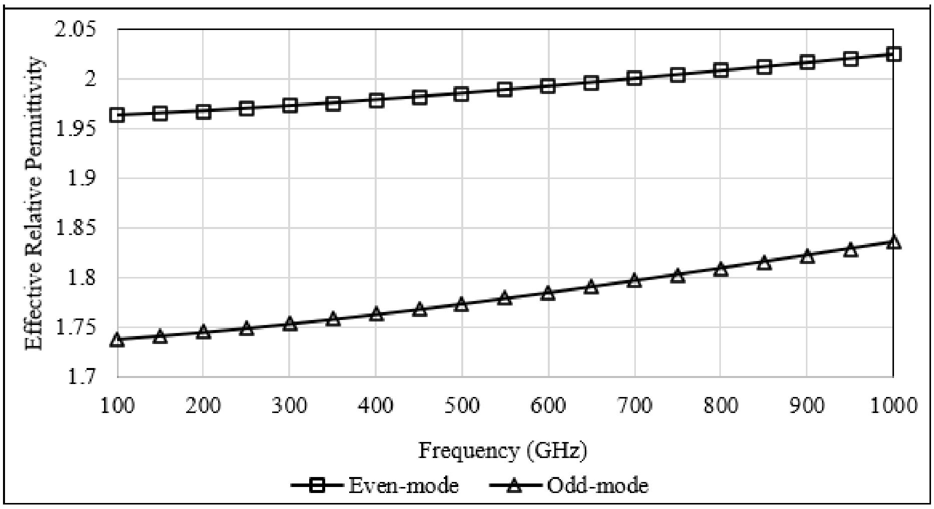

Figure 2(b): Effective Relative Permittivity E_{reff}, W=20µm, G=8.7µm.

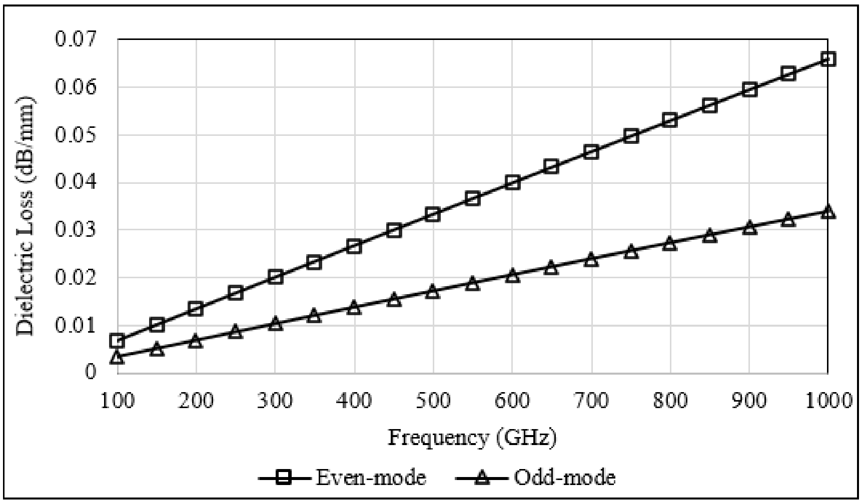

Figure 2(c): Dielectric Loss (dB/mm), W=20µm, G=8.7µm

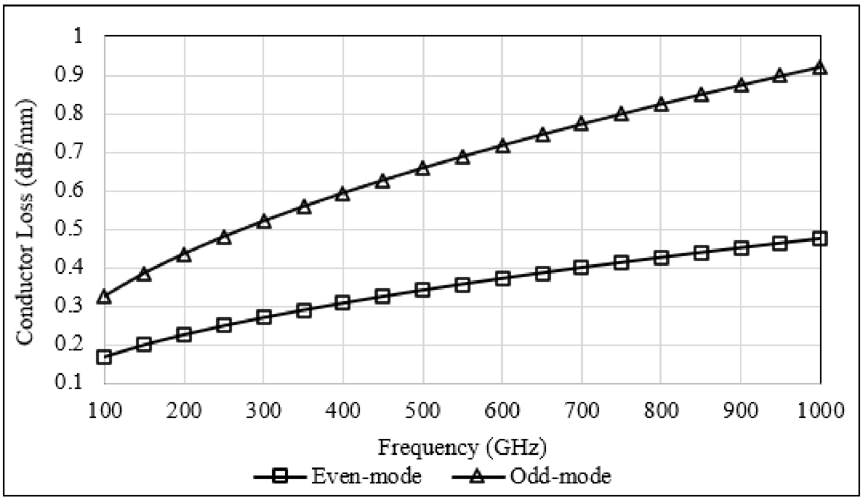

Figure 2(d) Conductor Loss (dB/mm), W=20µm, G=8.7µm.

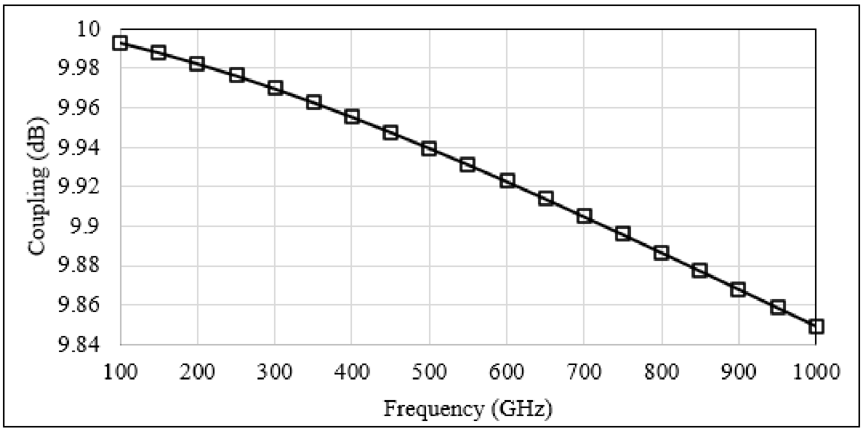

Figure 2(e): Coupling (dB), W=20µm, G=8.7µm.

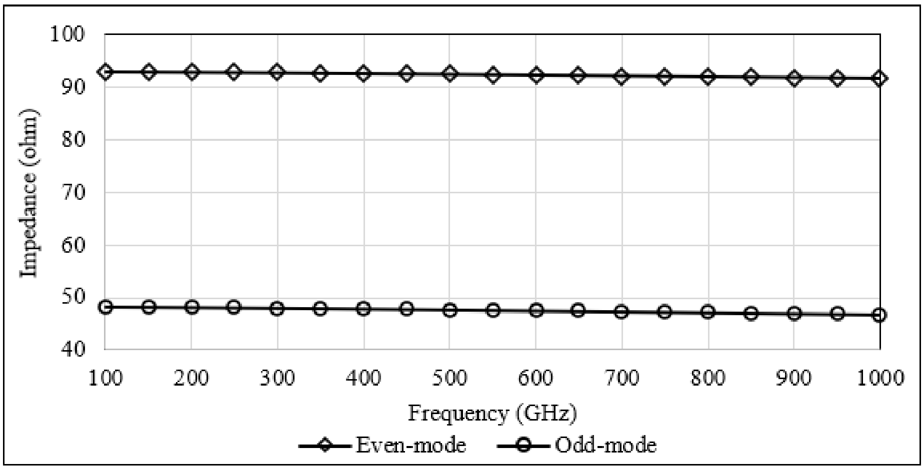

Figure 3(a): Impedance Zo (ohm), W=30µm, G=7.1µm.

Paper ID: SR241208105529 DOI: https://dx.doi.org/10.21275/SR241208105529

International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2023: 1.843

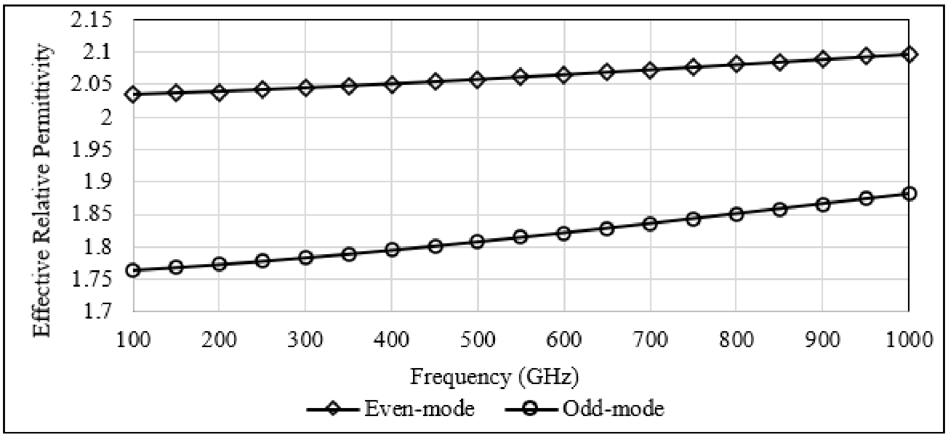

Figure 3(b): Effective Relative Permittivity E_{reff}, W=30μm, G=7.1μm.

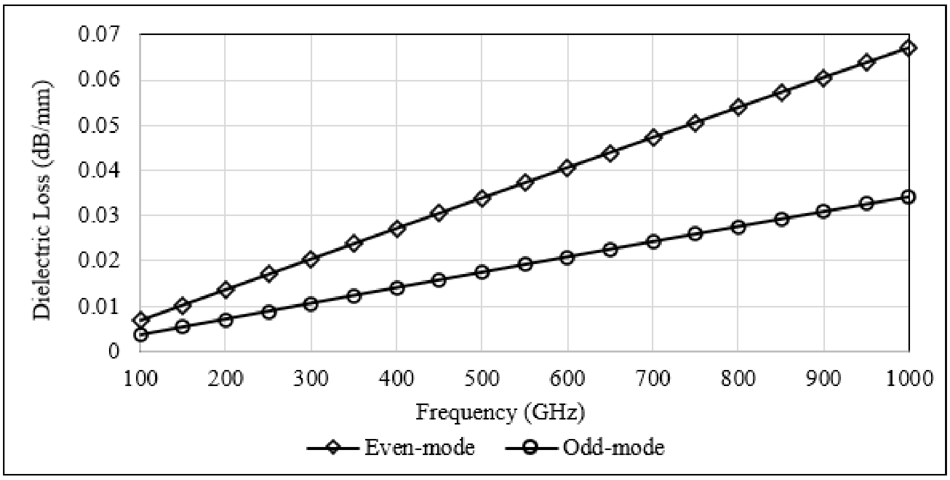

Figure 3 (c): Dielectric Loss (dB/mm), W=30μm, G=7.1μm.

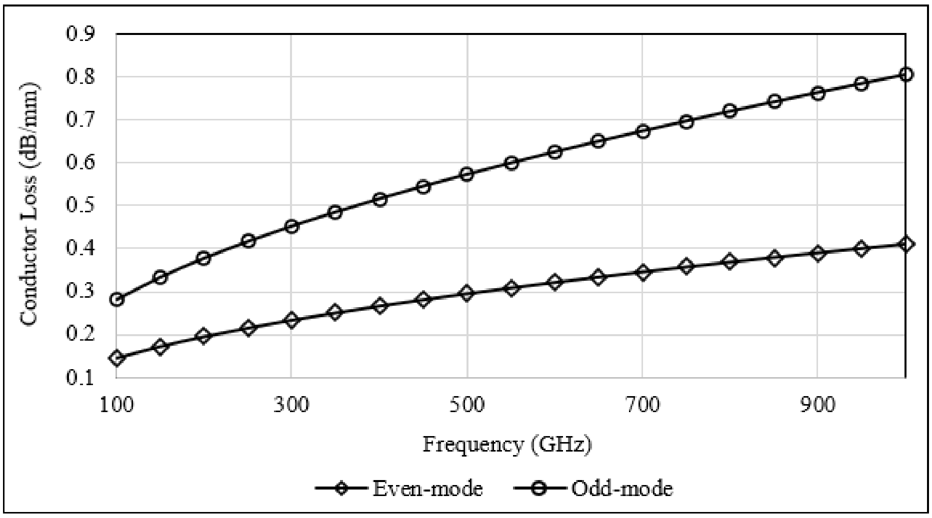

Figure 3(d) Conductor Loss (dB/mm), W=30μm, G=7.1μm.

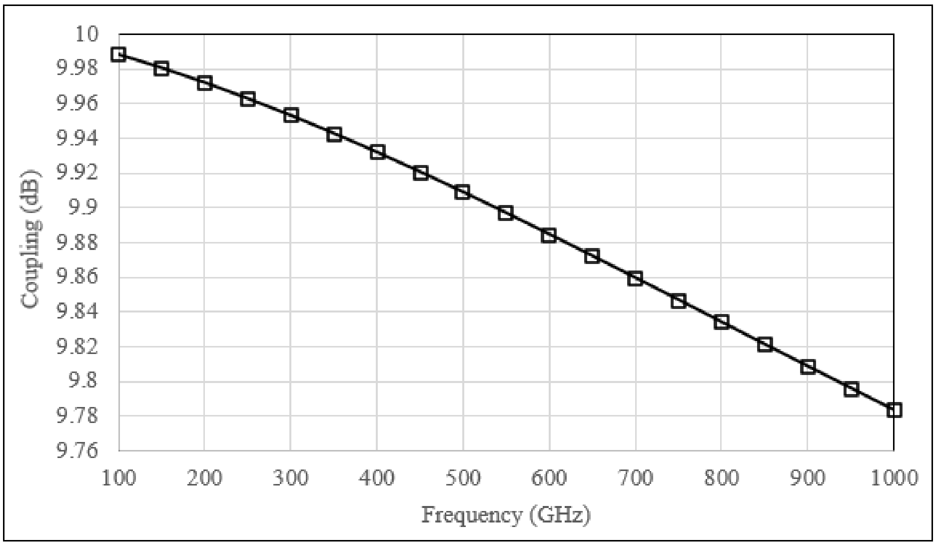

Figure 3 (e): Coupling (dB), W=30μm, G=7.1μm.

4. Conclusion

In this paper, impedance, effective relative permittivity, dielectric loss and conductor loss of thin film coupled microstrip line are computed from 100GHz to 1THz. For 10dB coupling, the variation in characteristic parameters of coupled microstrip line are analyzed. The coupled lines on thin film show very small variation in impedance and effective relative permittivity and these lines have potential to be used in broadband component design.

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