TEMPERATURE STABILITY FOR MICROSTRIP DELAY LINES ON HIGH PERMITTIVITY SUBSTRATES

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ABSTRACT

A constant time delay over temperature for miniaturized microstrip delay lines on high permittivity substrates is of great importance for many applications, particularly for space systems. A simple design formula helpful for the selection of a highly temperature stable substrate is presented. Moreover, a 274 ps delay line on CB substrate with a 0.40 % variation in time delay over the temperature range of -52 °C to +50 °C has been developed.

I. INTRODUCTION

Microstrip delay lines have many possible applications in today's world of high frequency communications and radar systems. High permittivity, or dielectric constant, substrates allow for the building of miniaturized microstrip delay lines which is advantageous in the present environment of compact microwave electronics. Therefore, the wise selection of high dielectric constant substrates is an imperative first step before a design can begin.

Previously, some work has been done in regards to producing temperature stable microstrip delay lines. Lee and Childs [1] employed two different substrates with opposing temperature coefficients of dielectric constant, α_ε. Since the α_ε of one substrate was positive and the other was negative, the α_ε of the overall circuit was almost zero by appropriate design. Thus very good temperature stability was achieved. Then, DeSantis [2] presented new design formulas intended to increase the range validity of the formulas given in [1].

Unfortunately, this approach requires the use of more than one type of substrate to build one delay line. In contrast, this paper will show that one substrate can be solely used to achieve a constant time delay over temperature if that substrate possesses the right properties. The substrate qualities necessary for low-loss, temperature-stable delay lines were determined through analysis. The results can be applied to other components.

II. DESIGN EQUATIONS

The time delay of a microstrip line is given by [3]

$$\tau_d = \frac{l\sqrt{\varepsilon_{eff}}}{c} \tag{1}$$

where l is the line length, c is the speed of light, and ε_{eff} is the effective dielectric constant given by [4]

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{w}\right)^{-1/2} +0.02(\varepsilon_r-1)\left(1-\frac{w}{h}\right)^2 \tag{2}$$

where ε_r is the relative dielectric constant, w is the width of the microstrip line, and h is the thickness of the substrate. The change in time delay over a temperature range is given by

$$\Delta\tau_d = \frac{1}{c}\left(l\Delta\sqrt{\varepsilon_{eff}}+\sqrt{\varepsilon_{eff}}\,\Delta l\right). \tag{3}$$

Equation (3) divided by equation (1) leads to

$$\frac{\Delta\tau_d}{\tau_d} = \frac{\Delta\sqrt{\varepsilon_{eff}}}{\sqrt{\varepsilon_{eff}}}+\frac{\Delta l}{l} \tag{4}$$

which represents the change in the time delay from the nominal time delay of the circuit.

The temperature coefficient of dielectric constant is given by [5]

$$\alpha_\varepsilon = \frac{\Delta\varepsilon_r}{\varepsilon_r\Delta T}. \tag{5}$$

Similarly, the linear thermal expansion coefficient is given by

$$\alpha_\ell = \frac{\Delta\ell}{\ell\Delta T}, \tag{6}$$

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where ℓ is the physical length of the substrate. Both of these properties of materials have units of ppm/K or 10^{-6}/K. It can be assumed here that l of equation (1) and ℓ of equation (6) will vary the same due to a change in temperature. Hereafter, ℓ will be used solely.

Equation (6) yields

$$\frac{\Delta\ell}{\ell} = \alpha_\ell \Delta T. \quad (7)$$

Using the property of differentiable functions, $\Delta\sqrt{\varepsilon_{eff}}$ is shown as

$$\Delta\sqrt{\varepsilon_{eff}} = \frac{1}{2\sqrt{\varepsilon_{eff}}}\Delta\varepsilon_{eff}. \quad (8)$$

Hence, both parts of equation (4) are obtained since

$$\frac{\Delta\sqrt{\varepsilon_{eff}}}{\sqrt{\varepsilon_{eff}}} = \frac{\Delta\varepsilon_{eff}}{2\varepsilon_{eff}}. \quad (9)$$

Now, $\Delta\varepsilon_{eff}$ can be found quite simply from (2) as

$$\Delta\varepsilon_{eff} = \frac{\Delta\varepsilon_r}{2} + \frac{\Delta\varepsilon_r}{2}\left(1+12\frac{h}{w}\right)^{-1/2} + 0.02\Delta\varepsilon_r\left(1-\frac{w}{h}\right)^2 + \left\{\left(\frac{\varepsilon_r-1}{2}\right)\left[-\frac{1}{2}\left(1+12\frac{h}{w}\right)^{-3/2}\right]\left(12\frac{w\Delta h - h\Delta w}{w^2}\right)\right\} + \left\{0.04(\varepsilon_r-1)\left(1-\frac{w}{h}\right)\left(-\frac{h\Delta w - w\Delta h}{h^2}\right)\right\}. \quad (10)$$

It can be reasonably assumed that any changes in h and w caused by α_ℓ will be the same. Using this assumption, the following equation is obtained:

$$w\Delta h - h\Delta w = w(h\alpha_\ell\Delta T) - h(w\alpha_\ell\Delta T) = 0. \quad (11)$$

Therefore, equation (10) reduces to

$$\Delta\varepsilon_{eff} = \frac{\Delta\varepsilon_r}{2}\left[1+\left(1+12\frac{h}{w}\right)^{-1/2}\right] + 0.02\Delta\varepsilon_r\left(1-\frac{w}{h}\right)^2. \quad (12)$$

Equation (12) divided by equation (2) results in

$$\frac{\Delta\varepsilon_{eff}}{\varepsilon_{eff}} = \frac{\frac{\Delta\varepsilon_r}{2}\left[1+\left(1+12\frac{h}{w}\right)^{-1/2}\right] + 0.02\Delta\varepsilon_r\left(1-\frac{w}{h}\right)^2}{\frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{w}\right)^{-1/2} + 0.02(\varepsilon_r-1)\left(1-\frac{w}{h}\right)^2}. \quad (13)$$

Now, if $\varepsilon_r >> 1$ then equation (13) can be simplified to

$$\frac{\Delta\varepsilon_{eff}}{\varepsilon_{eff}} \approx \frac{\frac{\Delta\varepsilon_r}{2}\left[1+\left(1+12\frac{h}{w}\right)^{-1/2}\right] + 0.02\Delta\varepsilon_r\left(1-\frac{w}{h}\right)^2}{\frac{\varepsilon_r}{2}\left[1+\left(1+12\frac{h}{w}\right)^{-1/2}\right] + 0.02\varepsilon_r\left(1-\frac{w}{h}\right)^2} \quad (14)$$

which can be further simplified to

$$\frac{\Delta\varepsilon_{eff}}{\varepsilon_{eff}} \approx \frac{\Delta\varepsilon_r}{\varepsilon_r}. \quad (15)$$

Substituting equation (15) into equation (9) and using equation (5), equation (9) becomes

$$\frac{\Delta\sqrt{\varepsilon_{eff}}}{\sqrt{\varepsilon_{eff}}} = \frac{1}{2}\alpha_\varepsilon \Delta T. \quad (16)$$

Finally, by using equations (16) and (7), equation (4) yields

$$\frac{\Delta\tau_d}{\tau_d} \approx \frac{1}{2}\alpha_\varepsilon\Delta T + \alpha_\ell \Delta T. \quad (17)$$

In order to obtain optimum temperature stability where the delay time will not deviate due to temperature changes, equation (17) must equal zero. This means that the type of substrate that will offer the maximum temperature stability will follow this simple equation:

$$\alpha_\varepsilon \approx -2\alpha_\ell. \quad (18)$$

III. DELAY LINE RESULTS

A substrate that matches well with the condition of equation (18) was used to produce extremely temperature-stable delay lines. This substrate called CB and made by Dielectric Laboratories, Inc. has previously been evaluated [6]. It is made from a magnesium titanate composite, has a relative dielectric constant of 29 and a loss tangent of 0.0004. This high dielectric constant can help to miniaturize the circuits. Furthermore, it has a α_ε of -10 ± 2 ppm/K and a α_ℓ of 6.3 ppm/K which is quite close to the condition of equation (18).

The microstrip delay line was processed by American Technical Ceramics, Inc. ATC metalized the substrate with gold, produced a glass photomask from an Autocad drawing, and etched the circuit. The delay line mounted on its test fixture is shown in Fig. 1. The circuit was designed using a 50 Ω line to produce a time delay of 274 ps at 7.75 GHz. The substrate thickness was 15 mils. Figs. 2(a) and (b) show the insertion loss, return loss, and time delay of the 274 ps delay line at room temperature. The insertion loss was fairly good except where it falls off at the high frequency end to less than 1.1 dB. On the other hand, the return loss was poor at barely greater than 10 dB at the high end. However, by modifying the circuit with tuning chips, as shown in Fig. 3, an insertion loss of less than 0.7 dB and a return loss of greater than 21 dB were obtained over a frequency range from 7.0 to 8.5 GHz.. The results are shown in Fig. 4.

The insertion loss and time delay characteristics of the 274 ps delay line over a temperature range from -52° C to +50° C are shown in Fig. 5. The change in insertion loss over temperature is about 0.3 dB. Most importantly, there is only a variation of 1.1 ps (or 0.4%) over temperature and at center frequency of 7.75 GHz. The variation is actually so small as to be negligible.

IV. CONCLUSIONS

A simple design formula useful for the selection of a highly temperature-stable substrate is presented. Using the formula, a suitable substrate, CB was selected. A 274 ps delay line was developed yielding a 0.40 % variation in time delay over the temperature range of -52 °C to +50 °C. The delay line performed well with an insertion loss less than 0.7 dB and a return loss greater than 21 dB.

V. ACKNOWLEDGMENTS

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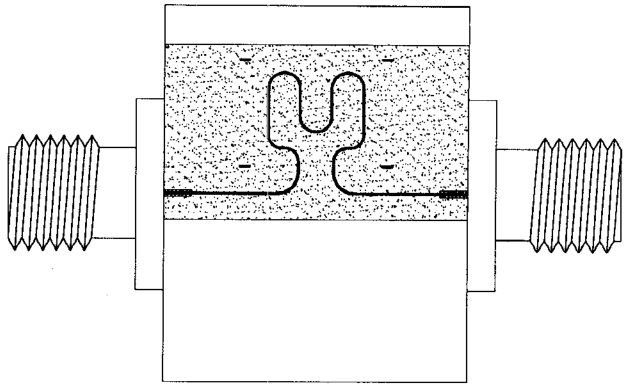


Fig. 1. A 274 ps microstrip delay line on CB substrate mounted on its test fixture. The boundary dimensions represented by the four dashes are 5.23 mm × 6.35 mm.

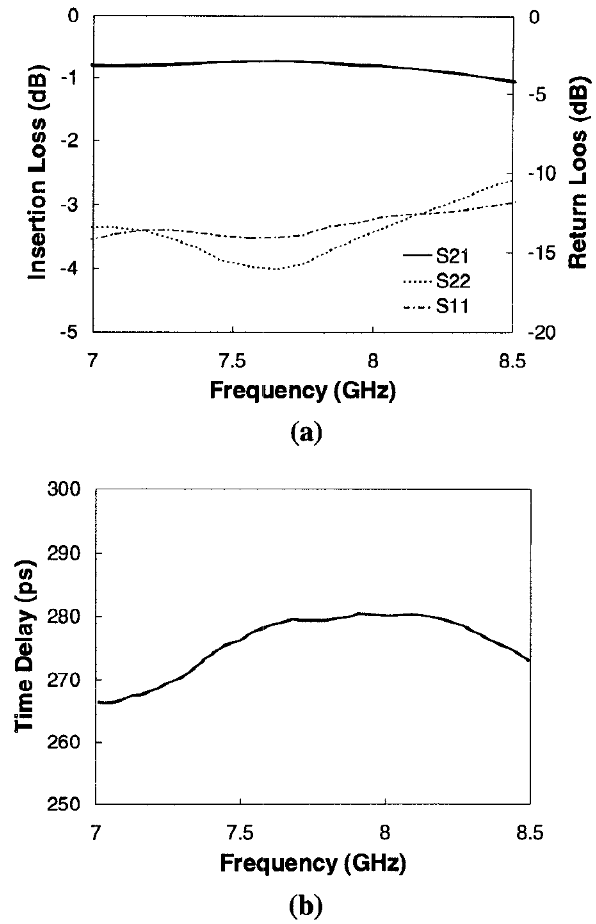


Fig. 2. The (a) insertion loss and return loss and (b) time delay of the 274 ps delay line measured at room temperature.

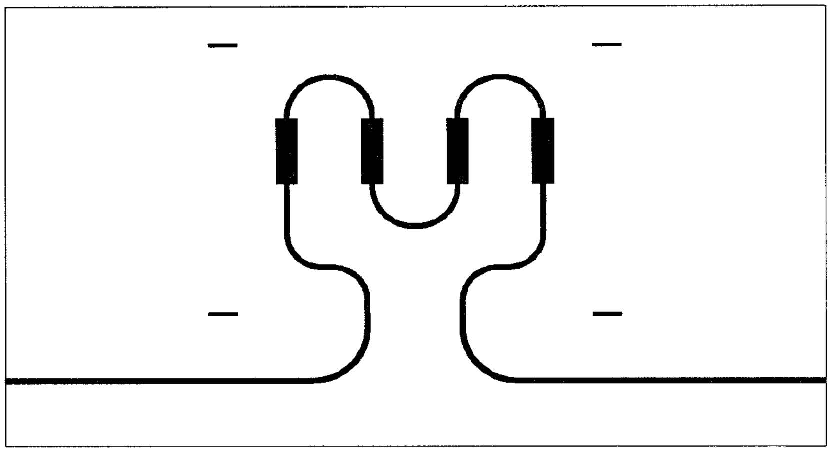
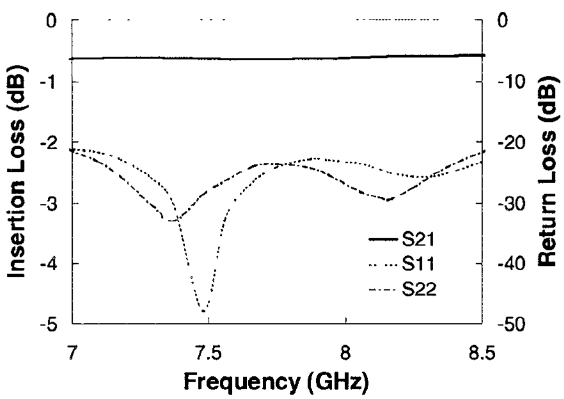
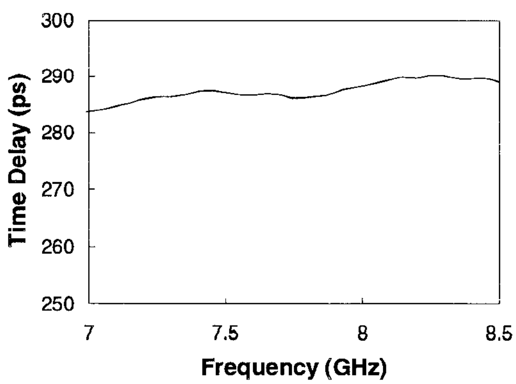


Fig. 3. A 274 ps microstrip delay line on CB substrate modified with tuning chips.

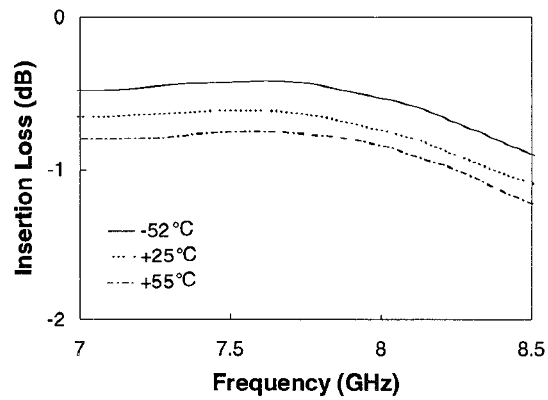


(a)

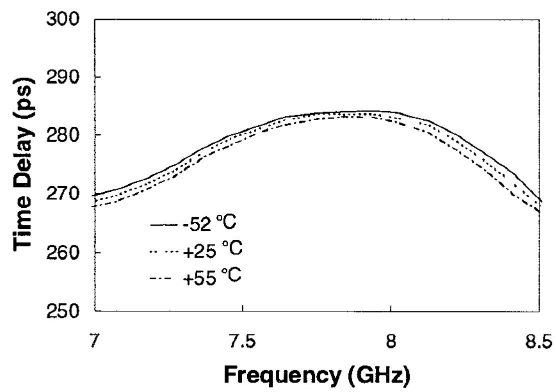


(b)

Fig. 4. The (a) insertion loss and return loss and (b) time delay of the modified 274 ps delay line at room temperature.



(a)



(b)

Fig. 5. The (a) insertion loss and (b) time delay of the 274 ps delay line measured over temperature.