TEMPERATURE-COMPENSATED $BaTi_4O_9$ MICROSTRIP DELAY LINE*

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ABSTRACT

A temperature-stable 16-ns delay element operating at 14 GHz has been developed using barium tetratitanate ($BaTi_4O_9$) ceramic microstrip lines with a short sapphire (single crystal $A\ell_2O_3$) microstrip section for temperature compensation. The measured transmission phase temperature coefficient of the delay element is +0.6 (±0.3) ppm/°C over the temperature range of 23°C ± 30°C.

Introduction

Microwave frequency signal processing is very attractive for future high-capacity digital communications satellite systems using onboard signal regeneration and switching techniques. A simple, passive, temperature-compensated, 16-ns microstrip delay line has been designed and experimentally evaluated for the implementation of a DQPSK regenerative repeater.[1-3]

Barium tetratitanate ($BaTi_4O_9$) ceramic substrate showed no material relaxation dispersion up to 18 GHz, and its microstrip characteristics, including microstrip dispersion and loss, showed excellent agreement with the theoretical prediction.[4] In the $BaTi_4O_9$ microstrip, the dielectric constant temperature coefficient is negative and the linear thermal expansion coefficient is positive; the resultant transmission delay phase temperature coefficient measured +3.9 ppm/°C at 14 GHz.

Conventional dielectric substrates, such as fused silica and sapphire,[5] have positive temperature coefficients both in the dielectric constant and in the linear thermal expansion. The transmission phase temperature stability in the sapphire (c-axis parallel to the electric field) microstrip measured -80.1 ppm/°C at 14 GHz. Thus, a short line section on the sapphire substrate can provide almost complete temperature compensation, resulting in a near-zero transmission phase variation in the $BaTi_4O_9$ microstrip line, when the line lengths are chosen correctly. This paper presents a simple design technique for the temperature-compensated microstrip delay element, which considered the microstrip dispersion effect in the group delay, and experimental results.

Design

The transmission phase temperature coefficient, $\alpha_{T,\phi}$, of an MIC line is determined mainly by the thermal expansion coefficient, $\alpha_{T,\ell}$, and the dielectric temperature coefficient, $\alpha_{T,\varepsilon}$, of the substrate material:

$$\alpha_{T,\phi} = -\left(\alpha_{T,\ell} + \frac{1}{2}\,\alpha_{T,\varepsilon}\right) \tag{1}$$

where $$\alpha_{T,\phi} = \frac{1}{\phi_o}\frac{\Delta\phi}{\Delta T},\quad \alpha_{T,\ell} = \frac{1}{\ell_o}\frac{\Delta\ell}{\Delta T}$$

and

$$\alpha_{T,\varepsilon} = \frac{1}{\varepsilon_r}\frac{\varepsilon_r}{\Delta T}$$

Table 1 lists the design parameters characterized on $BaTi_4O_9$ and sapphire substrates at 14 GHz.

Table 1. Design Parameters of $BaTi_4O_9$ and Sapphire Microstrip

Parameters	Substrates	
	$BaTi_4O_9$, Ceramic[a]	Sapphire, E//c-axis
Dielectric Constant, ε_r	37.0	11.5
Temperature Coefficient[b] (ppm/°C)		
Linear Expansion, $\alpha_{T,\ell}$	9.4	6.7
Dielectric, $\alpha_{T,\varepsilon}$	-26.6	141.0
Phase, $\alpha_{T,\phi}$	3.9[c]	-80.1[c]
Test Meandered MIC Line		
Impedance (ohms)	26.0	50.0
Substrate Thickness (in.)	0.015	0.015
Effective Dielectric Coefficient, ε_e (14.25 GHz)	26.2	7.6

[a] See Reference 4.
[b] For the temperature range of 23°C ± 30°C.
[c] Measured at 14.25 GHz.

The required group delay in the two substrate MICS, represented by the subscripts A and B, is determined as follows:

$$\tau_A + \tau_B = \tau_o \tag{2}$$

where τ_o is the total group delay specified.

The temperature-compensated delay phase condition is given by

$$\alpha_{T\phi,A}\tau_A + \alpha_{T\phi,B}\tau_B = 0 \tag{3}$$

The group delay of each microstrip line is determined from equations (2) and (3) as

$$\tau_A = \left|\frac{-\alpha_{T\phi,B}}{\alpha_{T\phi,A} - \alpha_{T\phi,B}}\right|\tau_o \tag{4a}$$

and

$$\tau_B = \left|\frac{\alpha_{T\phi,A}}{\alpha_{T\phi,A} - \alpha_{T\phi,B}}\right|\tau_o \tag{4b}$$

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From the required group delay, τ, the line length of each microstrip is then determined, considering the microstrip dispersion effect in the group delay:

$$\ell = v_g \tau \tag{5}$$

where the group velocity, v_g, is derived from Getsinger's microstrip dispersion relationship[6] as

$$v_g = \frac{v_p}{1 + \Delta(f)} \tag{6}$$

where v_p is the phase velocity given by

$$v_p = \frac{c}{\sqrt{\varepsilon_e(f)}} \tag{7}$$

and

$$\Delta(f) = \frac{\varepsilon_r - \varepsilon_e(0)}{\varepsilon_e(f)} \frac{G(f/f_p)^2}{\left[1 + G(f/f_p)^2\right]^2} \tag{8}$$

In equation (8), $\varepsilon_e(f)$ is as given in Reference 6:

$$\varepsilon_e(f) = \varepsilon_r - \frac{\varepsilon_r - \varepsilon_e(0)}{1 + G(f/f_p)^2}$$

and the terms are defined in References 4 and 6. In equation (7), c is the velocity of light in vacuum.

For a strip-width to substrate thickness ratio (W/H) of 1.0 (Z_o = 26.1Ω, ε_r = 37.0, and H = 0.015 in.) the computed value of Δ in the $BaTi_4O_9$ microstrip at 14.25 GHz is 0.077. Therefore, the group delay in the 26.1Ω $BaTi_4O_9$ microstrip line is 7.7 percent higher than the corresponding phase delay at 14.25 GHz.

Experimental Results

Figure 1 is a photograph of the composite, $BaTi_4O_9$ and sapphire, microstrip delay line assembly. The spacing between the adjacent folded lines was 13.2 times the substrate thickness. Thermal compression bonding of Au ribbons was used for line interconnection. Additional electrical shieldings were provided along the substrate interfaces with thin conductor shims integrated into the top lid of the assembly (not shown).

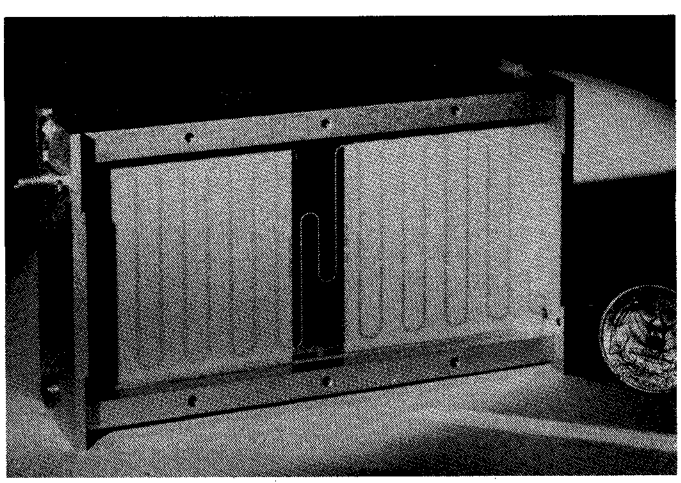

Figure 1. Microstrip Delay Line Assembly

Figure 2 shows a computer simulated time delay of the complete line of Figure 1. The computer model included the $BaTi_4O_9$ lines, the sapphire line, and transformer line sections, in which the loss and dispersion effects were taken into account rigorously. The upper curve in Figure 2 shows the group delay and the lower curve shows the delay computed using the phase velocity with ε_e(14.25 GHz).

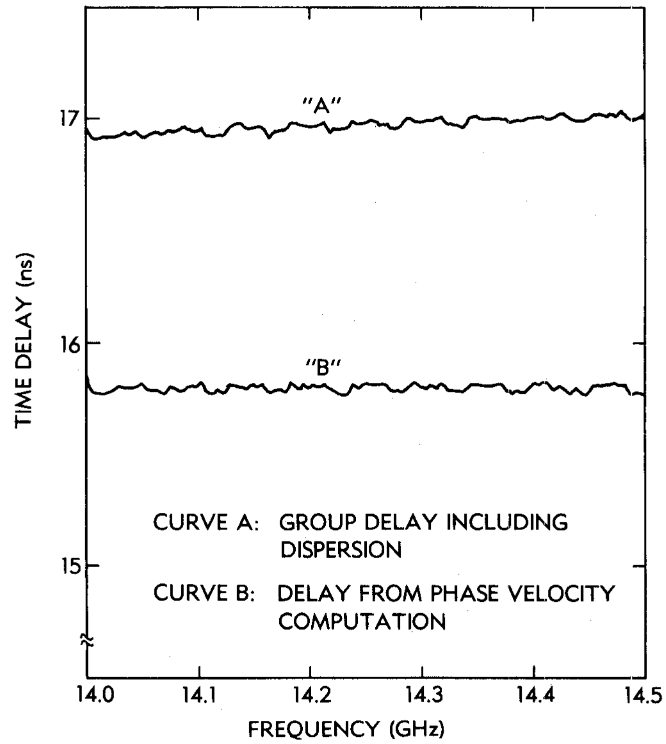

Figure 2. Computed Time Delay of the Line Shown in Figure 1.

In Figure 3, which gives the broadband group delay response of the circuit, the measured average group delay in the 14.0- to 14.5-GHz band is 16.8 ± 0.1 ns; this shows good agreement with the theoretical response (see the upper curve in Figure 2). The swept frequency transmission loss characteristic is shown in Figure 4. The insertion loss at 14.25 GHz is 23.6 dB, which agrees with the prediction.

Figure 5 shows typical temperature stability test data using the modified "Pi-point" method.[1] The average transmission phase temperature coefficient was computed for the temperature range of -6°C to 57°C at the 14-GHz band:

$$\alpha_{T,\phi} = 0.6\ (\pm 0.3)\ \text{ppm/°C}$$

The temperature stability measurement required a well-controlled thermal equilibrium condition in the composite substrate MIC assembly due to the thermal conductivity differences of about 20:1 in the sapphire and $BaTi_4O_9$.

The test result demonstrated that the microstrip delay line assembly had a good temperature-compensated performance. A near-zero temperature coefficient can be obtained with the present design technique, further considering quadratic temperature coefficient terms in the two substrates.

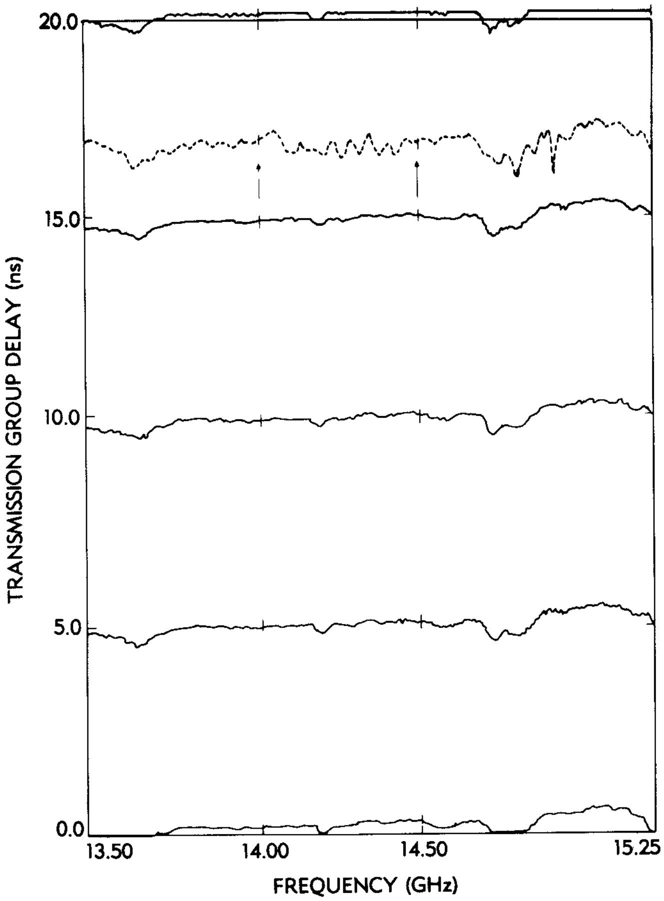

Figure 3. Measured Group Delay vs Frequency

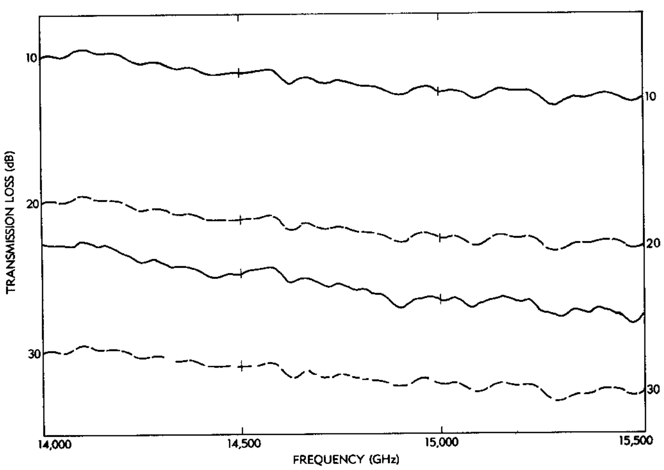

Figure 4. Transmission Loss Characteristic

Conclusion

A simple temperature-compensated design technique was applied in the development of a highly temperature stable 16-ns microstrip delay line at 14 GHz, using $BaTi_4O_9$ and sapphire substrates. The microstrip dispersion effect in the group delay was included in the design procedure. The delay line has a very broad frequency response and the measured transmission phase temperature coefficient is 0.6 ± 0.3 ppm/°C.

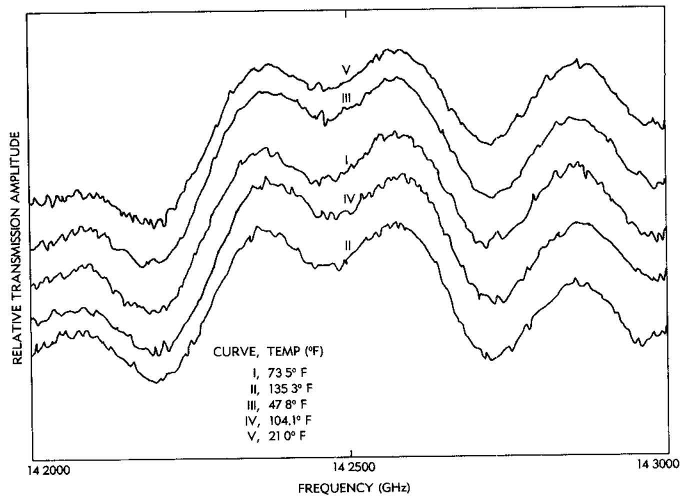

Figure 5. Temperature Stability Measurements

This paper demonstrates that the $BaTi_4O_9$ substrate can be used in highly temperature-stable, subminiaturized MIC component and subsystem designs, utilizing the high dielectric constant (ε_r = 37) and its small phase temperature coefficient.

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