14-GHZ MIC 16-ns DELAY FILTER FOR DIFFERENTIALLY COHERENT QPSK REGENERATIVE REPEATER*

Y. S. Lee
Member of Technical Staff
COMSAT Laboratories
Clarksburg, Md. 20734

ABSTRACT

A parallel-coupled microstrip fused silica filter at 14 GHz was developed as a 16-ns delay element for application to direct detection with a differentially coherent quaternary PSK (DQPSK) demodulator/regenerator module of an onboard regenerative repeater for future satellite-switched time-domain multiple-access (SS-TDMA) satellite communications systems. Design considerations, experimental results of the 14-GHz bandpass delay element, and a technique for precision measurement of the fused silica filter delay phase temperature coefficient are presented. In addition, the expected DQPSK demodulator performance is evaluated by simulation analysis using a comprehensive transmission channel modeling program.

Introduction

An onboard regenerative repeater for satellite-switched time-division multiple-access (SS-TDMA) systems has many well-known advantages.[1,2] One of the most important requirements for SS-TDMA applications is minimum acquisition time in carrier recovery. The implementation of a differentially coherent quaternary phase shift keying (DQPSK) detection regenerative repeater[1] avoids the necessity for carrier recovery.

Up-link frequency (i.e., 14.0- to 14.5-GHz band) direct detection of very high data rate ($\geq$120-Mbit/s) DQPSK signals eliminates the conventional IF stages including local oscillator chains for down-conversion. Compact, lightweight, highly reliable microwave integrated circuits (MIC) can be utilized for the design of an onboard regenerative repeater. A 14-GHz direct DQPSK demodulator requires an extremely stable delay element as a 1-symbol delay unit. A half-symbol delay element can also be used for the bit timing extraction.

This paper presents some of the design considerations and experimental results of a 14-GHz fused silica microstrip 16-ns delay bandpass filter. A technique has been developed for the precision measurement of the very small delay phase thermal coefficient of the fused silica filter. Finally, the comprehensive simulation analysis will demonstrate that the MIC delay filter can be used as a 1-symbol delay unit in a DQPSK demodulator with carrier-to-noise power ratio (C/N) degradation less than 0.2 dB at BER = 10^{-4} compared with an ideal delay line.

Design Considerations

If a 14-GHz up-link receive channel bandwidth-time product of 2 is used, a 120-Mbit/s DQPSK data signal will require a 120-MHz bandwidth. For this application an MIC bandpass filter can be used as a compact delay circuit of 1-symbol duration (16.67 ns).

Group delay is defined by $-d\phi/d\omega$, where ϕ is transmission phase in radian and ω, the angular radian frequency. The group delay at the bandcenter frequency in a narrow bandpass filter is initially estimated by[3]

$$\tau_0 = \frac{1}{\pi(f_2 - f_1)} \frac{1}{2} \sum_{k=1}^{N} g_k \qquad (1)$$

where g_k's are the filter prototype g-parameters, N is the number of poles, and f_2 and f_1 define the 3-dB transmission band.

A multi-stage cascaded high-order ($N \geq 10$) parallel-coupled microstrip filter was designed with the aid of the COMPACT program nodal analysis technique.[4] The open-end effects of the coupled lines were modeled using equivalent lumped capacitances,[5] and the circuit loss was approximated with an equivalent attenuator model in each of the $\lambda/4$-resonator elements.

The 16-ns MIC delay filter was developed as four 4-ns filters in cascade (Figure 1) on a single 15-mil-thick fused silica substrate (K_r = 3.8). Initially, the design of the 4-ns unit filter was evaluated on 10th order Bessel type and Chebychev type MIC bandpass filters. Test results indicated that the Bessel filter's theoretical group delay flatness was susceptible to the impedance matching condition, and its input/output characteristics were not symmetrical. A 0.01-dB passband ripple Chebychev filter's measured in-band group delay ripple component was larger than the Butterworth design. Therefore, the final unit filter was designed as a 10-pole Butterworth bandpass circuit with a 2.8-percent fractional bandwidth at the band center frequency 14.25 GHz.

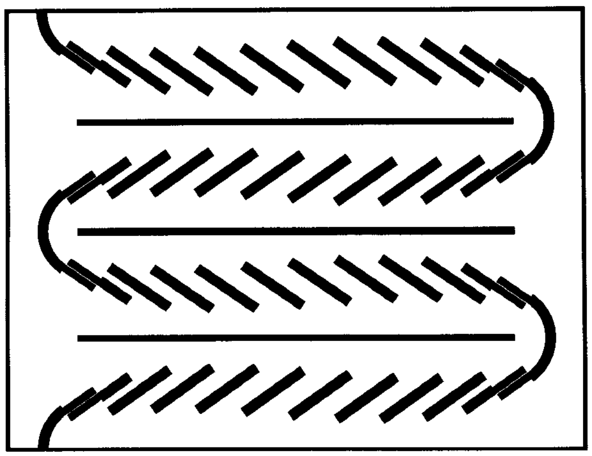

Figure 1. Artwork of 16-ns Delay Fused Silica MIC Filter

The complete 4-unit circuit was photo-etched on a 1.36- x 1.78-inch substrate installed in an Invar housing. Interstage electrical shielding between the unit filters was provided by additional thin shims, conductively epoxy-bonded through slots cut in the fused silica substrate.

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16-ns Delay Filter Characteristics

Transmission and Return Losses

The 16-ns delay filter is shown in Figure 1. Figure 2 is the transmission loss versus frequency characteristic of the filter, measured using an automatic network analyzer setup. Insertion loss is 17.5 dB at the band center frequency, 14.25 GHz. The 3-dB bandwidth is 305 MHz, and the 1-dB bandwidth is 185 MHz. Figure 3 is the transmission phase versus frequency response.

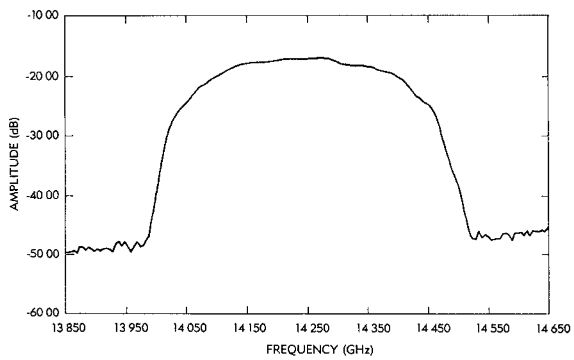


Figure 2. Transmission Loss Measurements

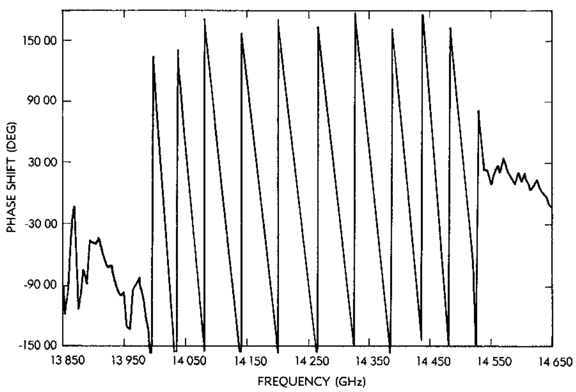


Figure 3. Transmission Phase Measurements

Typical in-band return loss is about 15 dB as shown in Figure 4. The data of Figures 2 thru 4 include the input/output connector discontinuities of OSM-244-4ASF wave launchers.

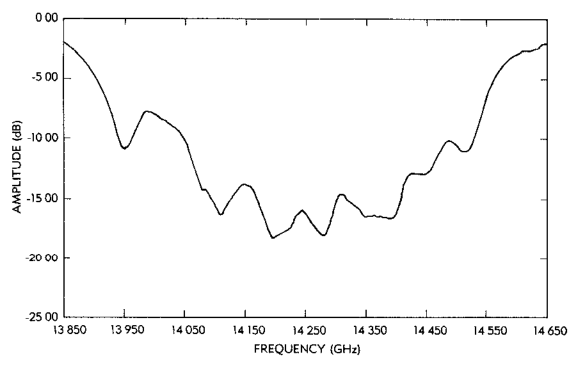


Figure 4. Return Loss Measurements

Group Delay

Rantec time delay equipment (ET-300 setup) was used for the swept frequency measurements of the group delay shown in Figure 5. The group delay at 14.25 GHz is 16.0 ns; the measurement accuracy is ± 0.1 ns. The measured peak group delay slope is 0.03 ns/MHz within the passband time product (BT) of 2. The parabolic group delay distortion at BT = 2 is about 3.7 percent.

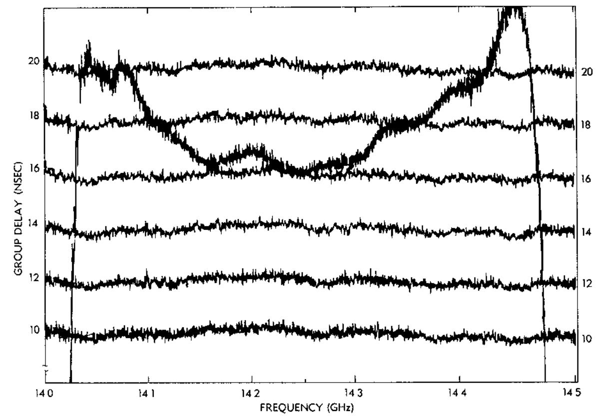


Figure 5. Group Delay Versus Frequency

Temperature Coefficient of Delay Phase

A "pi-point" method[6] was extended and developed for the precision measurement of the delay phase temperature coefficient near the band center frequencies in the fused silica MIC filter. This technique does not require any modification of the filter circuit and can be used to measure small values of phase thermal stability (i.e., <10 PPM/°C) with the high accuracy of frequency measurements. This concept is a new application of the cyclical variation of group delay in a transmission line with identical discontinuities.[7]

The delay filter is very loosely coupled to the external measuring circuit by a very small series of coupling capacitors (C_cs) shown in Figure 6. The transmission amplitude of the overall test circuit will be peaked at each frequency f_k where the transmission phase, ϕ, is a multiple of π(pi)-radians.

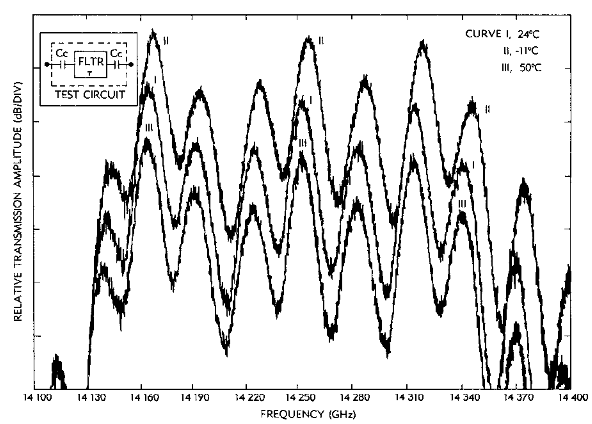


Figure 6. Thermal Stability Measurements

Delay phase is a function of frequency, ω, and temperature, T.

$$\phi = \phi(\omega, T) \tag{2}$$

The total differential is

$$d\phi = \frac{\partial \phi}{\partial \omega} d\omega + \frac{\partial \phi}{\partial T} dT \tag{3}$$

The maximum transmission frequency change is measured as temperature is changed. Since phase is always a multiple of π at a maximum transmission frequency, dϕ is zero. Thus,

$$\frac{\partial \phi}{\partial T} = -\frac{\partial \phi}{\partial \omega} \frac{d\omega}{dT} \tag{4}$$

Substituting $\tau = -\partial\phi/\partial\omega$ and expressing the changes in frequency and temperature as differentials during the measurement yields the temperature sensitivity of phase as

$$\frac{\partial \phi}{\partial T} = 2\pi\tau \frac{\Delta f}{\Delta T} \tag{5}$$

If equation (5) is normalized against $\phi_0 = \omega_0 \tau$, which is the total phase of a non-dispersive transmission line with the same delay as the filter, the temperature coefficient of delay phase is

$$\frac{\partial \phi}{\phi_0 \; \partial T} = \frac{\Delta f}{f_0 \; \Delta T} \tag{6}$$

Figure 6 shows the test circuit for the "pi-point" measurement. The external circuit C_cs at the input and output ports of the MIC filter were obtained by carefully adjusting the air gaps (∿ 30 mils) between the center tap of the connectors and the conducting strip of the 50-ohm microstrip lines. The insertion loss of this test arrangement is very high, about 55 dB including the filter circuit loss. A TWTA was added in the output port of the filter to obtain the appropriate signal level for the swept frequency measurement.

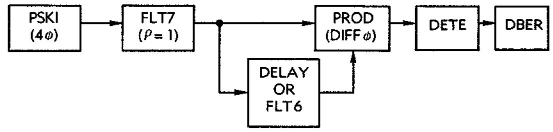
Figure 6 gives the measured data. The temperature coefficient of the delay phase is computed using equation (6) as -5.3×10^{-6}/°C near the band center frequencies. The corresponding transmission phase temperature sensitivity in the 16-ns delay filter is 0.45°/°C at 14.250 GHz.

The linear thermal expansion coefficient in the fused silica is 0.5 PPM/°C, and the thermal coefficient of the dielectric constant in the substrate is about 10 PPM/°C. The delay phase thermal stability is mainly determined by the dielectric constant thermal characteristic.

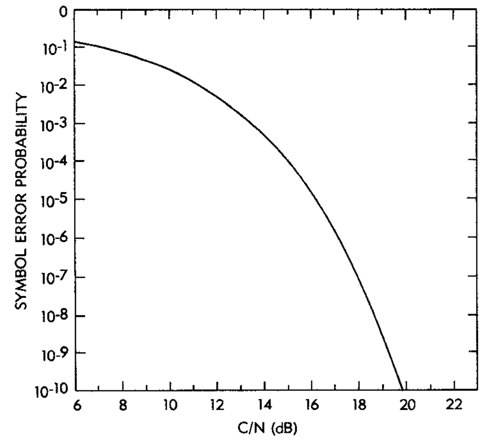
Simulated DQPSK Demodulator Performance

The average symbol error probability was computed for DQPSK detection[1] using the measured MIC delay filter characteristics for the synthesis of a 1-symbol delay unit in the demodulator. The simulation model (Figure 7a) was used for the expected system performance analysis with a COMSAT transmission channel modeling program.[8]

The channel filter was modeled as a cosine roll-off Nyquist filter with a unity roll-off factor, ρ = 1. The 1-symbol delay filter was synthesized as FLT6 using the measured amplitude and delay data of the previously described filter. Figure 7b is the computed symbol error rate curve. The C/N degradation due to the non-ideal delay characteristics of the MIC delay filter is negligible (less than 0.2 dB). Table 1 lists the computed C/N values at a symbol error rate of 1×10^{-4} and 1×10^{-9} in the ideal versus actual DQPSK demodulator/regenerators. Simulation accuracy is 0.4 dB in C/N.



(a) Simulation Model for DQPSK Detection



(b) Symbol Error Probability with the MIC 1-Symbol Delay Filter in DQPSK Demodulator

Figure 7. Simulation Model and DQPSK Detection Performance

Table 1. Comparison of C/N (dB) Values in Actual Versus Ideal DQPSK Demodulator

Channel Filter	Cosine roll off (ρ=1) Nyquist		Near ∞-Bandwidth
1-Symbol Delay Element Symbol Error Probability	MIC Delay Filter C/N (dB)	Ideal Delay Line C/N (dB)	Ideal Delay Line C/N (dB)
1×10^{-4}	15.14	14.97	14.73
1×10^{-9}	19.34	19.19	18.63

The required time delay of 1-symbol duration, T_S, in the DQPSK demodulator is $1/f_B$, where f_B is the symbol clock frequency. It should be related to the demodulator input RF frequency, f_c, such that $T_S = M/2f_c$, where M is an integer.

Conclusions

The simulation analysis showed that the 16-ns MIC delay filter can be used as a 1-symbol delay element for 14-GHz DQPSK detection. The measured temperature coefficient of the phase delay in the fused silica MIC filter is -5.3 PPM/°C at frequencies near the band center. The delay phase thermal coefficient is mainly determined by the dielectric thermal coefficient in the substrate material.

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