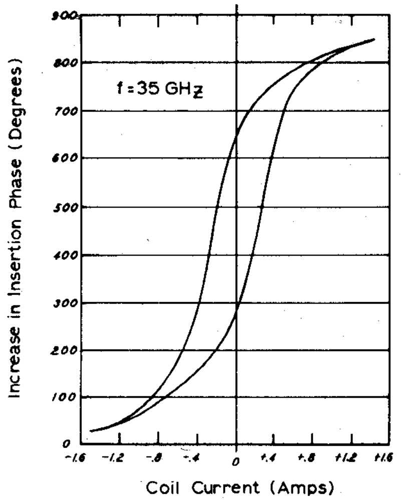

Fig. 2. Microwave hysteresis loop.

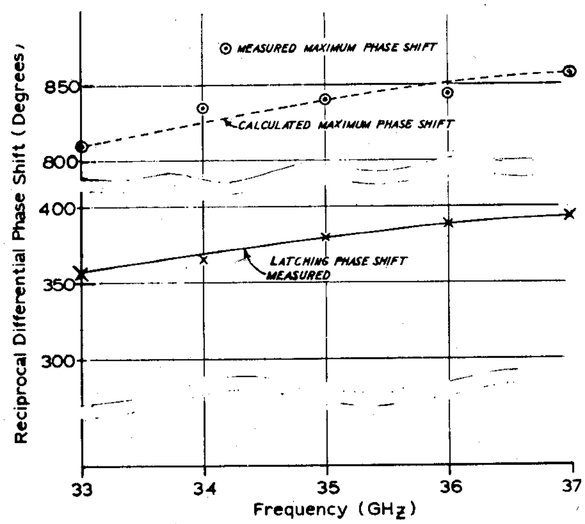

Fig. 3. Phase shift characteristics.

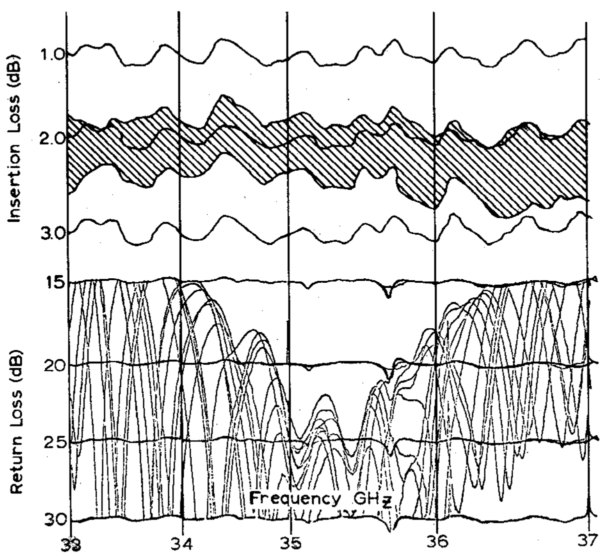

Fig. 4. Insertion and return loss.

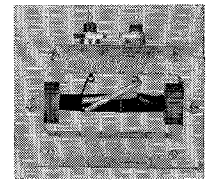

Fig. 5. Dual-mode phaser unit.

tion of the yoke structure. Insertion loss and match data are given in Fig. 4. An 18-dB return loss (1.3 VSWR) is obtained across approximately a 2-GHz band centered at 35 GHz. An insertion loss modulation larger than desired is obtained. This modulation results largely from an imperfect polarizer used in constructing this phaser. The modulation is expected to be reduced to approximately ± 0.2 dB in a second unit presently under construction. The obtained minimum values of insertion loss are in good agreement with the computational values shown in Table I. A photograph of the test unit is given in Fig. 5.

Conclusions

The dual-mode reciprocal phaser is well suited for millimeter wave switching and antenna utilization. The previously described unit is economical to fabricate and requires only standard tolerances in parts. Major fabrication problems are not anticipated at frequencies up to 100 GHz. The basic phaser shown in Fig. 5 may be made quite rugged and temperature-stable by encapsulating the open regions with a thermally conductive compound.

Acknowledgment

The authors wish to thank R. W. Jansen who fabricated the test phaser.

References

[1] R. A. Stern and J. P. Agrios, "A fast millimeter ferrite latching switch," in *1966 G-MTT Symp. Dig.*, pp. 219–223.
[2] L. R. Whicker, J. E. Degenford, and E. Wantuch, "Millimeter wavelength latching ferrite phase shifters," *1967 NEREM Rec.*, pp. 60–61.
[3] E. Wantuch, J. E. Degenford, and L. R. Whicker, "Modified nickel ferrites with high saturation magnetization and improved hysteresis properties," *J. Appl. Phys.*, vol. 39, Feb. 1969, pp. 723–725.
[4] C. R. Boyd, Jr., "A dual-mode latching, reciprocal ferrite phase shifter," in *1970 G-MTT Symp. Dig.*, pp. 337–340.
[5] C. R. Boyd, Jr., L. R. Whicker, and R. W. Jansen, "An S-band, dual mode reciprocal ferrite phaser for use at high power levels," in *1970 G-MTT Sym. Dig.*, pp. 346–350.
[6] J. J. Green, "Microwave properties of partially magnetized ferrites," RADC Tech. Rep. TR-69-338.

Wide-Band Microwave Acoustic Delay Line with Exceptionally Smooth Phase and Loss Response

W. R. SPERRY, E. K. KIRCHNER, AND T. M. REEDER

***Abstract*—Design techniques for high-performance microwave delay lines which have superior bandwidth, phase linearity, and spurious echo characteristics are presented. Utilization of these techniques to realize a 4-μs *L*-band unit which has insertion loss of 30 ± 0.5 dB over the 500-MHz band centered at 1.7 GHz, with triple-transit suppression greater than 45 dB and phase deviation from linearity of less than $\pm 2.5°$, is described.**

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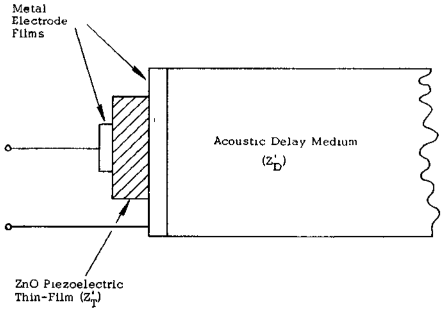

Fig. 1. Schematic view of the thin-film acoustoelectric transducer.

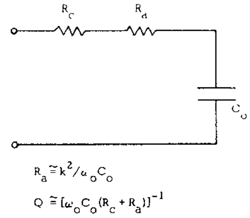

Fig. 2. Approximate equivalent circuit for the thin-film transducer

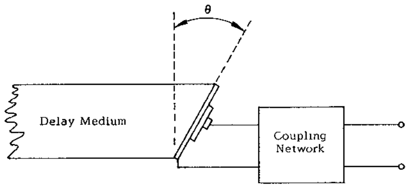

Fig. 3. Schematic view of a delay line showing the beveled face technique for enhancing TTS.

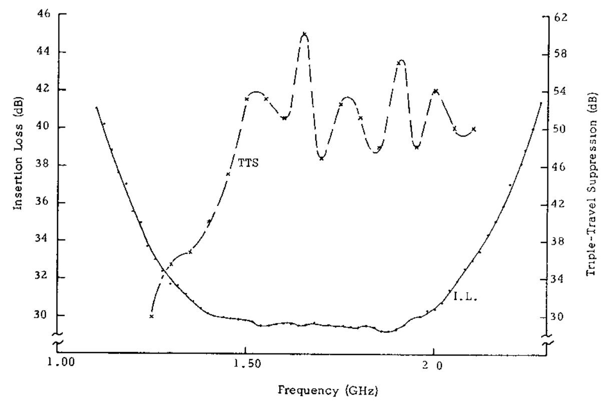

Fig. 4. Insertion loss and TTS versus frequency for the 4-μs delay line.

Microwave acoustic delay lines, because of their potentially wide bandwidth and relatively low insertion loss [1], have long been proposed as high data rate, signal storage devices. Until very recently, however, technological problems have resulted in devices which fell far short of the predicted bandwidth and loss. This correspondence describes a design approach which allows the bandwidth, phase linearity, and spurious signal suppression to be optimized. The design of a high-performance 4-μs unit operating at L band is used to illustrate the techniques.

Design of microwave acoustic delay lines can be divided into five areas.

Selection of an acoustic delay medium consistent with the requirements of signal delay, insertion loss, and spurious signal suppression.

Design of efficient acoustically broad-band transducers for acoustoelectric conversion.

Realization of electromagnetic tuning and coupling networks to provide broad-band transducer operation with minimum insertion loss.

Design of the delay medium and transducer geometry to enhance the suppression of spurious signals.

Construction of a package to provide stable mechanical and temperature environment, the latter being important for phase stability.

For an L-band delay line using longitudinal acoustic waves, a sapphire delay medium with propagation along the C axis is a good choice for signal delay in the 0.1- to 10-μs range. This choice is based on the observation that sapphire has relatively low acoustic loss and can be readily obtained in lengths required for long signal delay. Since the longitudinal wave velocity in C-oriented sapphire is 11.2×10^5 cm/s, a crystal length of 4.48 cm is required for 4-μs delay.

For efficient acoustoelectric conversion over a broad frequency range, the piezoelectric film transducer [2] has been found most suitable for microwave delay line operation. This type of transducer, shown schematically in Fig. 1, consists of metal and piezoelectric thin films which are vacuum deposited directly onto each end of the delay medium. For broad-band operation, the piezoelectric layer should have an acoustic impedance (Z_T') just slightly less than that of the acoustic delay medium (Z_D') [3]. Piezoelectric ZnO films are a good choice for sapphire delay lines, not only because of their appropriate acoustic impedance, but also because of their high piezoelectric activity leading to low conversion loss [4].

The electrical input impedance of the thin-film transducer imposes a severe problem in achieving broad-band operation. As shown in Fig. 2, the electrical equivalent circuit consists of a series combination of geometrical capacitance (C_0), a radiation resistance (R_a) and electrode conduction resistance (R_c). The quality factor Q is given by the expression in Fig. 2 where ω_0 is the radian center frequency and k is the electromagnetic coupling factor. The problem is that the Q of this circuit, for typical transducers, is on the order of 10. To achieve low-loss operation, tuning elements are needed to resonate this highly reactive impedance. One finds a compromise between network insertion loss and bandwidth for bandwidths greater than $1/Q$ [5], [6]. Although standard network design techniques [7] have been successfully applied to the design of broad-band transducer matching networks [3], [8] these methods typically used a multielement transmission-line circuit which in practice is difficult to fabricate. A somewhat simpler approach has been developed, consisting of shunt resonators coupled by quarter-wavelength transmission lines. By choice of the network impedance level, a maximally flat or small ripple response can be obtained with a 3-dB fractional bandwidth appreciably greater than $1/Q$.

The suppression of spurious echoes in a volume-wave delay line poses another design problem. For wide-band operation, the thin-film transducers present a high reflection boundary condition. Thus the signal pulse may be reflected many times within the delay medium unless appreciable propagation loss exists or geometrical loss is created. In the development of the L-band unit described herein, a combination of propagation loss, diffraction loss, and delay path geometrical design was used to optimize the suppression of triple-transit signals. Propagation loss for the sapphire delay medium provides only a small amount of triple-transit suppression (TTS) since only 2 dB of loss is incurred in mid L band for 4 μs of delay. By proper choice of the transducer aperture, another 9.55 dB of TTS is obtained through diffraction loss. Hence for the L-band unit, the largest contribution to TTS was provided using geometrical loss as explained in the following.

TTS can be enhanced by using an angled (beveled) end face as shown by the diagram of Fig. 3. The angle, θ, is chosen to place the null in the radiation pattern of the triple-transit signal, launched at

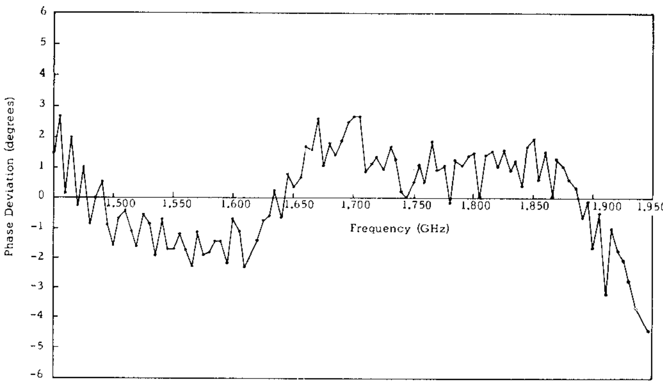

Fig. 5. Phase deviation from linear for the 4-μs L-band delay line.

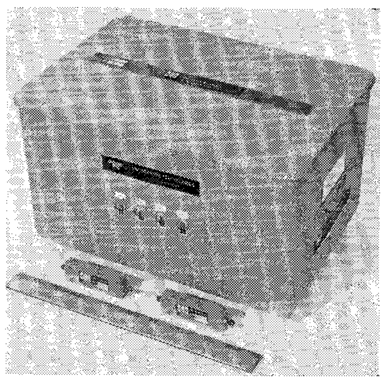

Fig. 6. Photograph showing the identical 4-μs L-band delay lines and temperature stabilizing oven.

the input transducer aperture, at the position of the output transducer aperture. The null location is frequency dependent; thus the angle is determined at the center operating frequency. Theory for propagation along the C axis of sapphire (including the anisotropy) predicts that 33-dB TTS can be achieved over a 33.2-percent bandwidth using this geometrical loss technique. For the 4-μs delay line, with a bevel angle of 43.2 min, TTS in excess of 46 dB is achieved over the 500 MHz centered at 1.7 GHz, as shown in Fig. 4.

The beveled end face, however, increases the loss of the desired delay signal and causes a loss slope with frequency. For the 4-μs delay line with a 43.2-min angle the additional loss incurred due to the angle is 6 dB at 1.45 GHz and 13 dB at 1.95 GHz. This loss slope plus the slight increase in slope due to the propagation loss dependence on frequency is compensated by the diffraction loss due to the input transducer aperture plus tuning to give the flat insertion loss response shown in Fig. 4. The insertion loss of this unit, which averages 30 dB, is flat within 0.5 dB over the 500-MHz bandwidth centered at 1.7 GHz.

Since the delay medium is nondispersive, the phase characteristic of a microwave acoustic delay line would be linear except for phase ripple caused by the acoustoelectric transducers and associated coupling networks, or, in CW operation, by the presence of a triple-transit signal. The phase ripple of a passive network is low if the insertion loss is close to a maximally flat response [9]. For TTS greater than 45 dB, the phase ripple in CW operation due to the triple-transit signal is less than 0.5°. Tuning the matching network for maximally flat response yielded a phase ripple, for the 4-μs delay line, of less than $\pm 2.5°$ from linearity as shown by the data of Fig. 5.

If it is to be useful in microwave systems, a delay line must be packaged with a suitably stable mechanical and thermal environment. The package must also provide shielding to suppress unwanted electromagnetic feedthrough. To determine the necessary thermal environment, CW phase measurements were made on the 4-μs delay line when enclosed in an oven with temperature stability of 0.01°C. The test frequency was stabilized to one part in 10^9 and measured to better than one part in 10^7. Phase was measured with a network analyzer to $\pm 0.6°$. For the 4-μs delay line, which has a path length of approximately 2.4×10^6 degrees, it was found that an oven stability within 0.01°C was necessary to limit the insertion phase drift to $\pm 1°$. Fig. 6 is a photograph of two identical 4-μs delay lines with the characteristics described here, plus a constant temperature oven used to mount the delay lines to limit the phase drift to less than $\pm 5°$ with ambient temperature changes of ± 5°C.

Thus wide-band microwave acoustic delay lines with exceptionally smooth phase and loss responses can be achieved by careful attention to the design techniques described here. These techniques were utilized in achieving 4-μs delay lines with insertion loss of 30 ± 0.5 dB over the 500-MHz band centered at 1.7 GHz, with TTS greater than 45 dB, and with phase deviation from linearity of less than $\pm 2.5°$.

References

[1] F. A. Olson, "Today's microwave acoustic (bulk wave) delay lines," *Microwave J.*, vol. 13, Mar. 1970, pp. 67–76.
[2] N. F. Foster, G. A. Coquin, G. A. Rozgonyi, and F. A. Vannatta, "Cadmium sulphide and zinc oxide thin-film transducers," *IEEE Trans. Sonics Ultrason.*, vol. SU-15, Jan. 1968, pp. 28–41.
[3] T. M. Reeder and D. K. Winslow, "Characteristics of microwave acoustic transducers for volume wave excitation," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, Nov. 1969, pp. 927–941.
[4] E. K. Kirchner and R. A. Wilson, "Manufacturing technology for superior microwave acoustic transducers," A.F. Materials Lab., A.F. Syst. Command, Wright-Patterson AFB, Ohio, Tech. Rep. AFML-TR-70-99, June 1970.
[5] H. W. Bode, *Network Analysis and Feedback Amplifier Design*. New York: Van Nostrand, 1945, pp. 360–70.
[6] R. M. Fano, "Theoretical limitations on the broadband matching of arbitrary impedances," *J. Franklin Inst.*, vol. 249, Jan.–Feb. 1950, pp. 57–84 and 139–154.
[7] G. L. Matthaei *et al.*, *Microwave Filters, Impedance Matching Networks, and Coupling Structures*. New York: McGraw-Hill, 1964, ch. 11.
[8] T. M. Reeder and F. A. Olson, "Wideband impedance matching of microwave transducers," presented at 1968 IEEE Ultrasonics Symp., New York, Sept. 1968, Paper L-8.
[9] F. E. Terman, *Radio Engineering*. New York: McGraw-Hill, 1947, ch. 6.

The Ring-Loaded Corrugated Waveguide

YOSHIHIRO TAKEICHI, TSUTOMU HASHIMOTO, AND FUMIO TAKEDA

***Abstract*—The ring-loaded corrugated waveguide is shown to be very effective for frequency broadbanding of the waveguide and improvement of the transformer between the corrugated and uncorrugated waveguides.**

I. Introduction

The ring-loaded corrugated waveguide is one devised for the improvement of characteristics of the conventional corrugated waveguide. The corrugated waveguide is applied to the primary horn of a reflector antenna for satellite-communication earth stations to achieve higher efficiency and lower noise temperature [1], [2], but the useful frequency bandwidth of the conventional corrugated waveguide, in which it is effective for the improvement of antenna property, is restricted to about one octave. Besides this, useful frequency bandwidth becomes narrower if good matching is required between the corrugated and uncorrugated waveguides. In the ring-loaded corrugated waveguide, the useful frequency bandwidth is about 1.8

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