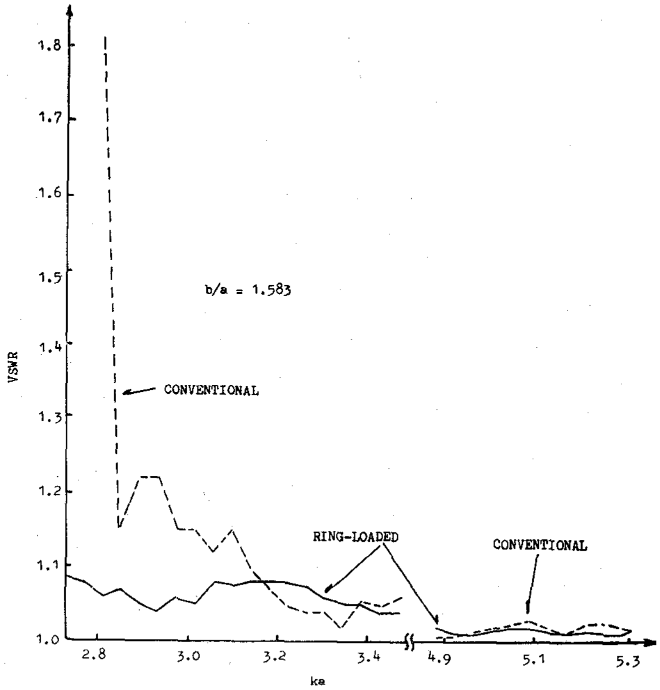

Fig. 5. VSWR for the transformers shown in Fig. 4(a) and (b).

quency bandwidth of the transformer made of ring-loaded corrugated waveguide section is remarkably broader than that of the conventional transformer.

IV. Conclusion

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

References

[1] G. H. Bryant, "Propagation in corrugated waveguide," *Proc. Inst. Elec. Eng.*, vol. 116, Feb. 1969, p. 203.
[2] P. J. B. Clarricoats, "Theoretical analysis of cylindrical hybrid modes in a corrugated horn," *Electron. Lett.*, vol. 5, May 1969, p. 187.
[3] A. F. Kay, "The scalar feed," TRG Sci. Rep. 5, 1964, Appendix A1, prepared for Air Force Cambridge Research Laboratories, Office of Aerospace Research, Bedford, Mass., under Contract AF 19(604)-8057.
[4] G. Saxon, T. R. Jarvis, and I. White, "Angular-dependent modes in circular corrugated waveguide," *Proc. Inst. Elec. Eng.*, vol. 110, Aug. 1963, p. 1365.

Controllable Liquid Artificial Dielectrics

H. T. BUSCHER, R. M. McINTYRE, and S. MIKUTEIT

***Abstract*—A novel approach to microwave phase control, utilizing liquid artificial dielectrics, is described. These media have been fabricated with permittivities which vary in magnitude and anistropy according to the strength of an applied electric control field. Continuously controlled permittivity increases of at least 20 percent in the electric field direction are realizable in liquid suspensions having low loss and very high dielectric strength. A simple waveguide liquid dielectric phase shifter has been built at *Ku* band and its operating characteristics measured. This approach can be applied to the design of electrically variable microwave lenses, power dividers, and resonant cavities as well as phase shifters.**

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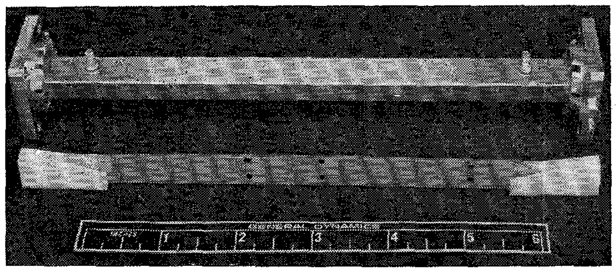

Fig. 1. Phase shifter, showing main control electrode and impedance matching wedges.

Introduction

In connection with phased array research, there has been considerable interest in developing low-cost electronically controlled microwave phase shifters. An economical way to accomplish this is to find a good dielectric with electrically controllable permittivity that can be inserted in the signal path and biased to cause the desired phase delays. This correspondence describes work with suspensions of metallic particles in high dielectric strength liquids. Such suspensions were found to constitute a class of dielectrics with sufficiently large microwave Kerr effect to be useful in practical devices. The physical mechanism of the dielectric's operation is outlined and performance data are presented for a 360° *Ku*-band waveguide phase shifter utilizing the Kerr effect in a liquid suspension [1].

Discussion

The permittivities of the media investigated could be changed by applying a low-frequency electric biasing field. The physical interaction responsible was similar to the one that occurs between light and pure liquids in the optical Kerr effect. In essence, suspensions were constructed as models of Kerr liquids scaled to the microwave region. While the controllable birefringence of a pure Kerr liquid is due to polarization and ordering of its molecules by an applied electric field, the artificial dielectrics used for this study achieved variable microwave birefringence as a result of induced polarization and alignment of their relatively larger solid components. Thus the asymmetric micron-size suspended solids corresponded to individual molecules of a pure Kerr liquid.

Early in this work, a brief search was made for simple liquids composed of large molecules which could show a directly useful Kerr effect at microwave frequencies. Such liquids may exist, but the suspension modeling approach quickly uncovered enough new ground to fully occupy available research personnel.

In order to simultaneously optimize suspension stability and response time, the addition of surfactants was found to be required. Some of these surface-active chemicals, however, tended to increase losses. Searching for components that minimized the cost of this sort of tradeoff produced two practical artificial dielectrics. Both were electrically similar, but one used fluorocarbon and the other hydrocarbon components. The data presented here are based on the more easily reproducible hydrocarbon system, made of benzene loaded with 8 mg/cm^3 of 1-μ diameter aluminum platelets and 16 mg/cm^3 of alkyl polyoxyethylene-amine.

All measurements were made using the cell shown in Fig. 1, which was designed as a *Ku*-band phase shifter. The electrode shown in front of the cell was normally supported in the H plane in the center of the guide, with a fine wire connecting it to an external feedthrough. When voltage was applied to the lead an electric field was impressed on the artificial dielectric in the microwave E plane. This caused an increase in permittivity for the TE_{10} mode, so propagation time for that mode increased with applied voltage. Liquid was retained in the guide by thin Mylar end windows. The Teflon wedges shown tapered the liquid column and thereby afforded a smooth impedance transition to the rest of the circuit.

The developmental artificial dielectrics described here underwent gradual settling if left at rest. To avoid this, they were cir-

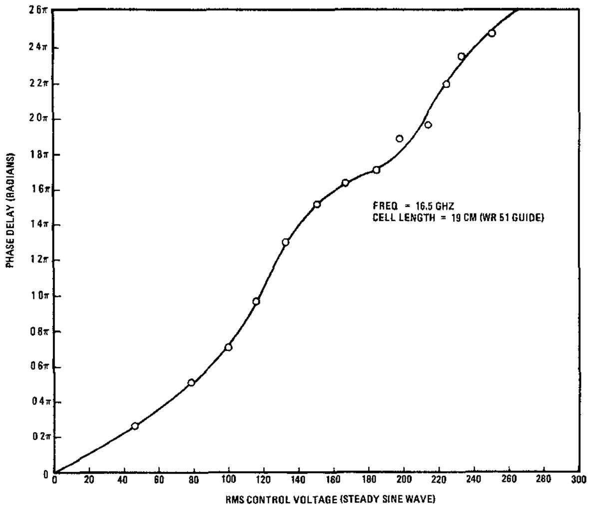

Fig. 2. Relative phase delay of device as a function of steady-state control voltage.

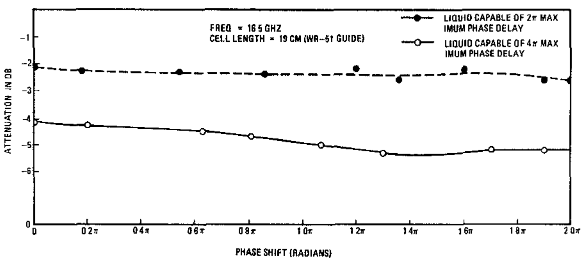

Fig. 3. Power loss of phase shifter for two liquid dielectrics as a function of steady-state controlled phase delay.

culated at 1 cm^3/s through small tubes in the broadwall to stabilize their electrical properties. Although control fields could have been dc or ac, 15-kHz sine waves were used for this work to preclude sweeping of any residual free ions. No conduction current was required to control the dielectrics.

When microwave signals having E-field amplitude comparable to that of the control field were sent through the cell, there could in theory have been an increase in phase delay due only to the signal. To avoid this, the rotational inertia of the suspended particles was adjusted so that they could reorient only in times long compared to the signal pulsewidth. In this way, signals much larger than the control field could be accurately delayed. The cell shown here operated successfully at more than 60-kW peak, 60-W average power in the 15- to 18-GHz band.

The change in phase delay through the cell with control voltage at 16.5 GHz is shown in Fig. 2. The change in phase delay was approximately proportional to the change in permittivity over the range of the data. Thus the permittivity of the artificial dielectric was almost linearly proportional to the applied control field. The dielectric constant changed by 7×10^{-4}/rms V/cm of control field.

Loss was essentially frequency independent. VSWR was less than 1.2:1 over the band. The dashed curve in Fig. 3 shows absorption loss with increasing controlled phase delay for a suspension having half the loading concentrations of the one normally used. The solid

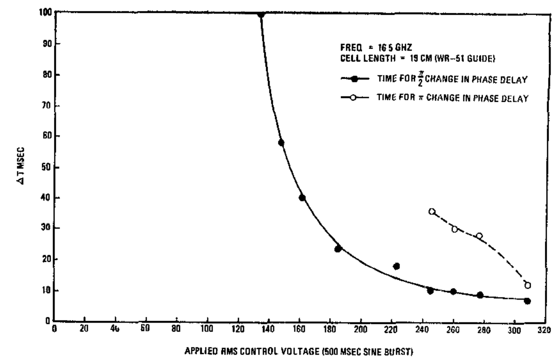

Fig. 4. Response time of phase shifter as a function of control voltage amplitude.

curve is for the standard liquid used for all other data. Probably neither depends strongly on control field because absorption was due to inherent loss in the benzene and residual water. The waveguide shell and epoxy-fiberglass electrode supports contributed 1.2 dB of the losses.

When a control field was applied to the artificial dielectric there was a short time lag before a new permittivity was established. If a field larger than that required to cause a given phase delay in the steady state was applied, the time to reach that phase delay was then considerably reduced. Fig. 4 shows the time lag to reach phase delays of $\pi/2$ and π versus control voltage amplitude. The shape of the curves may reflect increasing drag force opposing particle alignment as particle rotation speed increases.

Conclusion

A class of media which exhibit a useful Kerr effect in the microwave region of the spectrum has been found. Controllable liquid artificial dielectric (CLAD) materials have been constructed from easily available inexpensive components and tested in a waveguide phase shifter configuration at *Ku*-band frequencies. The waveguide device tested allowed 360° continuous phase control with less than 1.2:1 VSWR and 3-dB insertion loss from 15 to 18 GHz. Response time on the order of milliseconds was obtained with several hundred volts control potential and negligible control current. The device showed no breakdown when operated with a pulsed microwave input of 60-kW peak, 60-W average power.

Suspensions as control media offer great flexibility at low cost and would seem to be capable of high power handling capacity over a very wide frequency range. While much development remains to be done, work with pilot materials has shown no serious obstacles to continued improvement in performance. Investigation of the specific nature of the interaction between microwaves and the chemical charge layer (micelle) surrounding each suspended particle could be profitable [2]. Interesting work could also be done on the use of high dielectric constant solids as loading material and on synthesizing chemical systems other than simple suspensions as controllable dielectrics.

References

[1] W. Heller, "The origin and the complications of electric double refraction and of electric dichroism in dilute dispersed systems," *Rev. Mod. Phys.*, vol. 14, 1942, pp. 390–409 (includes bibliography).

[2] C. T. O'Konski and S. Krause, "Theory of the Kerr constant of rigid conducting dipolar macromolecules," *J. Phys. Chem.*, vol. 74, 1970, pp. 3243–3250 (includes bibliography and listing of original source papers on Kerr effect).