Electrically Controllable Liquid Artificial Dielectric Media

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Abstract—New work is reported on electric field controlled liquid dielectrics demonstrating their application in control devices at 35 and 95 GHz. Liquid artificial dielectric design approaches and performance prediction are also discussed, with emphasis on electronic beam steering of millimeter-wave antennas. References are included listing much of the prior work done in this area.

I. Introduction

THERE HAS BEEN a continuing awareness for several decades that many military radar and seeker systems would benefit greatly in performance if fast, simple electronic scanning antennas were available. It has proven quite difficult and costly, especially in the millimeter-wave region, to implement inertialess-scanning antennas.

In the late 1960's, two classes of microwave liquid artificial dielectrics were invented in the hope of overcoming the problems inherent in conventional approaches to antenna beamsteering [1]–[6]. The liquids were designed to change permittivity in response to an applied electric control field.

This property allowed analog delay-type phase shifters and dielectric prisms with electrically controllable refraction to be built at high microwave frequencies. Extremely high-power handling capacities and short response times were achieved under laboratory conditions with some liquids in 360° phase shifter configurations. A typical liquid might require 750-V/cm control field to produce a 30° phase shift per wavelength of path. Control current is negligible.

This paper reports new work on controllable liquid artificial dielectric (CLAD) media, with emphasis on millimeter-wave device applications. Basic principles of operation and liquid dielectric composition are discussed in Section II. Experimental data on new liquid dielectrics useful in the millimeter-wave region are presented in Section III, and device designs based on CLAD media are treated in Section IV.

II. CLAD Operating Principles

It has been known since the 1870's that many solids, liquids, and gases had dielectric constants that would change in response to large applied electric fields. While this effect was first discovered by J. Kerr in the optical region of the spectrum, it was soon found to exist for lower frequency radiation as well. The effect was extremely small and difficult to detect for most materials, but it was found that certain simple liquids, such as nitrobenzene, made up of asymmetric, highly polarizable molecules, exhibited the largest Kerr effects. In the 1930's, the first work on the optical Kerr effect in colloids and suspensions was performed. In the early 1950's, the relatively large and reproducible effects in these media formed the basis for several now well-developed diagnostic techniques in chemistry [7].

The basic principle behind the Kerr effect is that an applied electric field will polarize and partially orient asymmetric molecules or particles of a dielectric and thereby make its permittivity anisotropic. The usual result is an increase in permittivity for incident waves polarized parallel to the applied field. The effect goes as the square of the field according to

$$n_{\parallel} - n_{\perp} = B\lambda_0 E^2$$

where $n_{\parallel}$ and $n_{\perp}$ are the indices of refraction for waves with electric field vectors polarized parallel and perpendicular to the applied field E, λ_0 is the wavelength in vacuum, and B is the Kerr "constant." (In actuality, B varies with pressure, temperature, and λ_0.) As the applied field is removed, restoring forces act with a characteristic relaxation time to again randomize the medium to an isotropic dielectric.

Nearly all the work up to the last decade was done in pure liquids or aqueous media which showed either negligible Kerr effect in the microwave region, or strong absorption, or both. In order to exploit the effect in a practical microwave device, it was necessary to find media with low microwave losses and microwave Kerr constants which were enormous compared to those of known optical media. At the same time, it was thought desirable to retain the high breakdown strength and fast response times of the optical media.

So far, two approaches have produced dielectrics showing useful microwave properties. Both depend on scaling up the size and polarizability of molecules in liquids similar to optical Kerr media. The first approach is to suspend highly asymmetric, micrometer-size metallic particles in a low-loss base liquid, and the second is to form solutions of high molecular-weight rigid macromolecules. Data on both types of media have been published, but by

Manuscript received July 17, 1978; revised November 29, 1978.
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0018-9480/79/0500-0540$00.75

TABLE I
MILLIMETER-WAVE DIELECTRIC CONSTANTS AND LOSS TANGENTS FOR POTENTIAL CLAD SOLVENTS (ALL BETWEEN 20° AND 28°C)

SOLVENT		FREQUENCY (GHz)					
		19.25	20.0	33.9	35.0	97.0	142.0
CYCLOHEXANE	κ:	2.013 ①		2.014 ①			2 02 ③
	TAN δ.		6 X 10^{-5} ②		9 X 10^{-5} ②		9 X 10^{-6} ③
n-HEXANE	κ.						
	TAN δ:		5.3 X 10^{-4} ②		7.8 X 10^{-4} ②		
n-HEPTANE	κ:				1 91 ④		1.92 ③
	TAN δ		6.4 X 10^{-4} ②		7.9 X 10^{-4} ②		4 1 X 10^{-4} ③
n-NONANE	κ·						
	TAN δ.		6 3 X 10^{-4} ②		6 9 X 10^{-4} ②		
n-DECANE	κ.						
	TAN δ·		1 03 X 10^{-3} ②		1 03 X 10^{-3} ②		
BENZENE	κ	2 27 ①			2 3 ④		2 28 ③
	TAN δ·				1.25 X 10^{-3} ④		3 2 X 10^{-3} ③
CARBON TETRACHLORIDE	κ	2.23 ①			2 13 ④		2.24 ③
	TAN δ:				1 25 X 10^{-3} ④		2.5 X 10^{-3} ③
CARBON DISULPHIDE	κ·						
	TAN δ.				8 X 10^{-4} ⑤		
ETHYLBENZENE	κ.					2.25 ⑥	
	TAN δ.					< 0.02 ⑥	
BROMO-TRICHLORO-METHANE	κ·					2.37 ⑥	
	TAN δ:					< 0 02 ⑥	
FC-75 (3-M)	κ.				2. ⑦		
	TAN δ:				4 X 10^{-3} ⑦		
FC-77 (3-M)	κ:				2 ⑦		
	TAN δ.				4 X 10^{-3} ⑦		

① VAN LOON (1973)
② DAGG & REESOR (1972)
③ GARG et al (1965)
④ MAKHIJA (1971)
⑤ HARVEY (1963)
⑥ RAMPOLLA (1959)
⑦ THIS AUTHOR (1977)

far the greatest effort has gone into the metallic-suspension approach.

The remainder of this paper will concentrate primarily on this latter approach because it is experimentally easier to investigate.

Metallic suspensions useful in the microwave region have been known for about eight years, but handling and stability problems that discourage production applications still exist. Low-loss base liquids (such as benzene) are often both flammable and toxic, and the commonly available metallic particles are too large to form stable suspensions without constant agitation.

To this author's knowledge, data on CLAD media specifically designed for use in the millimeter region have not yet been reported. In regard to simplicity, loss reduction, and cost savings, the potential advantages of CLAD-based devices in the millimeter region are at least as great as in the microwave range while the suspension design is not appreciably harder.

The *a priori* requirement for constructing useful millimeter-wave CLAD media is that low-loss low viscosity solvents exist for that region. The experimental data in Table I demonstrate that a number of candidates are available. Liquids having loss tangents smaller than about 5×10^{-3} could be used as bases for practical millimeter-wave suspensions, resulting in typical device losses less than about 2.5 dB. Dagg and Reesor (Fig. 1) have shown that a theory by Debye can be used to predict losses in many of the Table I liquids throughout the millimeter region [8]. It can be seen that losses in some pure liquids are actually expected to decrease with frequency above about 30 GHz.

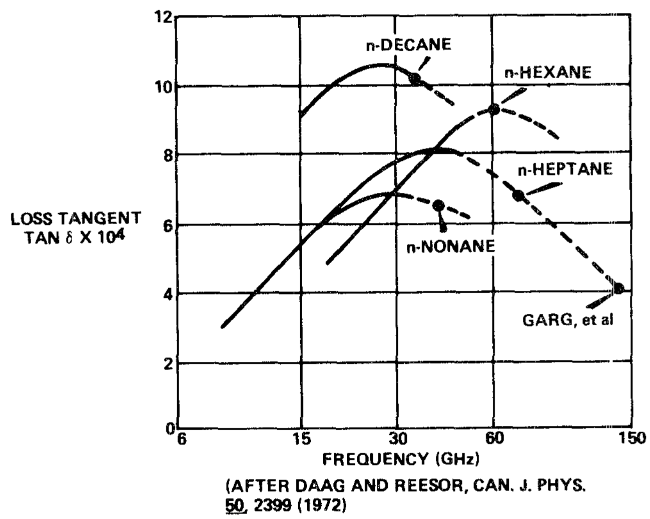

Fig. 1. Debye-type curves fitted to data for four alkanes.

Losses for complete CLAD media are not so easily predicted, although it is probably true that they will increase with the volume fraction of metallic suspensoid, with the size of the suspended particles, and with contamination by any polar or ionic species [9], [10].

Dielectric constants of the CLAD media can be estimated from the Clausius–Mossotti relations. O'Konski has derived an expression for the Kerr constant of a metallic suspension based on the polarizabilities of its constituents [10], [7].

Response and relaxation times for suspensions of asymmetric polarizable particles can be calculated from the work of a number of authors (a summary is given in O'Konski [7]).

In general, analytic descriptions exist for most CLAD properties, given the characteristics of the constituents and the ability to combine them without unknown amounts of agglomeration. The use of surfactants as stabilizers in these nonionic-nonaqueous systems is usually required in order to see any appreciable Kerr effect, but surfactant selection is still mainly by trial and error.

III. Experimental Results

In order to demonstrate the feasibility of using CLAD media in the millimeter-wave region, three new media were constructed. Measurements of the properties of each were made at 35 GHz, and one liquid was characterized at 94 GHz. The suspensoid for each was commercially obtainable aluminum paint pigment. The base solvents (selected from Table I) were n-heptane and a fluorocarbon sold under the trade name FC-75 (3M Corporation). The surfactants showing the greatest dispersing effect for each medium were selected from a large group of commercial products by experiment. (The exact composition of each of the three CLAD media formulated is listed along with its performance in Figs. 3–6.)

All 35-GHz data were taken using a simple WR-28 waveguide cell, similar to that shown in Fig. 2. The liquid-filled section was 8.9 cm long; the central phosphor-bronze electrode was 8.4 cm long, 6.35 mm wide, and 0.08 mm thick. The electrode supports were 0.51-mm thick Teflon. No portion of the Teflon impedance-matching wedges extended into the liquid region. A flat 0.01-mm Mylar seal and a single-sided wedge were used at each end of the cell. In addition, holes 1 mm in diameter were drilled in the center of the guide broad wall near each end of the cell to allow filling and continuous 10-ml/min circulation of the fluid during data collection. Liquid temperature was about 30°C for all data.

The central fin electrode was connected, by a 0.2-mm wire as shown, to a 20-kHz ac sinusoidal voltage supply. By varying this supply relative to the guide walls, a (rather nonuniform) polarizing electric field could be imposed on the CLAD medium in the cell. The complete cell had a VSWR of less than 1.10:1 for all filling media and a combined leakage and conduction loss of 0.7 dB. Quantities observed by using standard techniques were phase shifts through the cell caused by the polarizing voltage, and one-way loss for the filled cell. The calibrated range of the reference phase shifter available for taking this 35-GHz data was slightly over 200°, and the control voltage supply was capable of 160-V rms.

Fig. 3 shows phase shift through the cell versus applied voltage for a CLAD material based on n-heptane. The shape of the curve probably reflects the gradual alignment of the wide range of particle sizes present in the aluminum suspensoid as well as the beginnings of saturation of the Kerr effect. Since the loss in the CLAD medium was essentially constant at 1.2 dB, it could be inferred that 360° phase shifters could be produced with about 2.4-dB loss using this electrode geometry, requiring less than 140 V for control. Or, a higher control voltage could be applied, producing phase shift at constant 1.2-dB loss until saturation was reached.

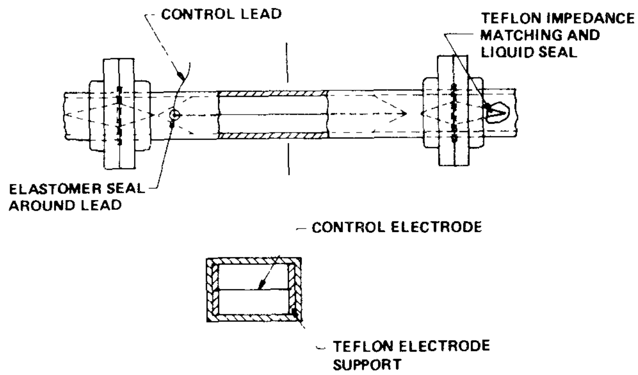

Fig. 2. Discrete liquid phase shifter in waveguide (from U.S. Patent 3 805 197).

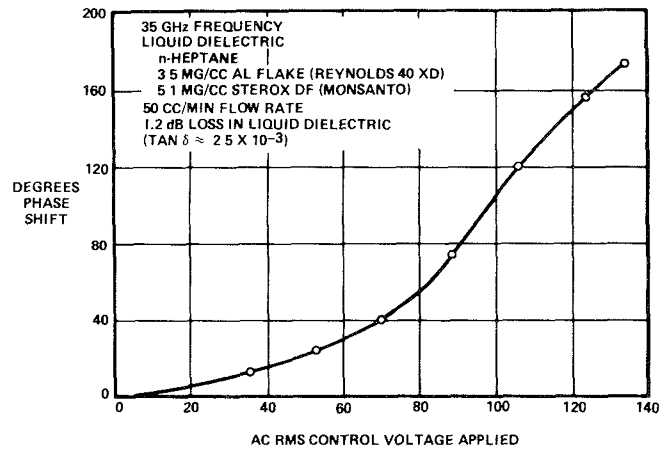

Fig. 3. Phase shift versus applied voltage, single-electrode WR-28 cell 8.9 cm long.

Fig. 4 shows the performance of another n-heptane-based liquid as the concentration of aluminum particles is reduced. The increased loss compared with the liquid of Fig. 3 is not due to the surfactant used *per se*, but to the presence of larger agglomerations of particles.

These more symmetric agglomerations also cause earlier saturation of the Kerr effect with applied field than occurs for more complete dispersion. This can be seen by noting that saturation is reduced for 1.75-mg/cm^3 aluminum loading by increasing the surfactant concentration and thus the degree of dispersion.

While n-heptane has relatively low loss, it is also flammable and toxic. Unlike the chlorinated hydrocarbons, it is not reputed to react spontaneously with metal powders, but it is far from an ideal material for our purposes. The

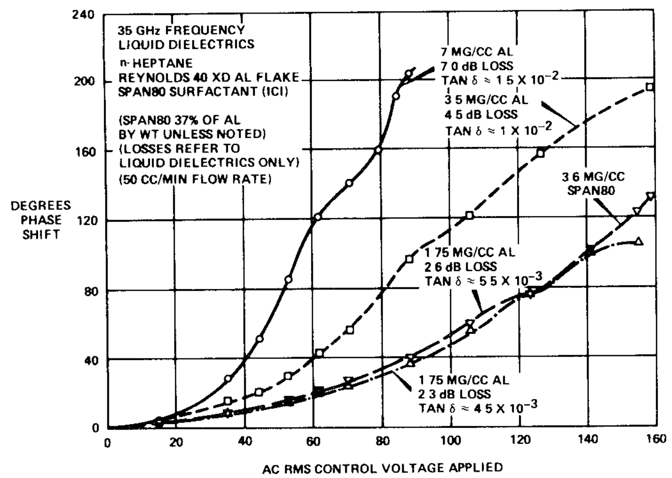

Fig. 4. Phase shift versus applied voltage, single-electrode WR-28 cell 8.9 cm long.

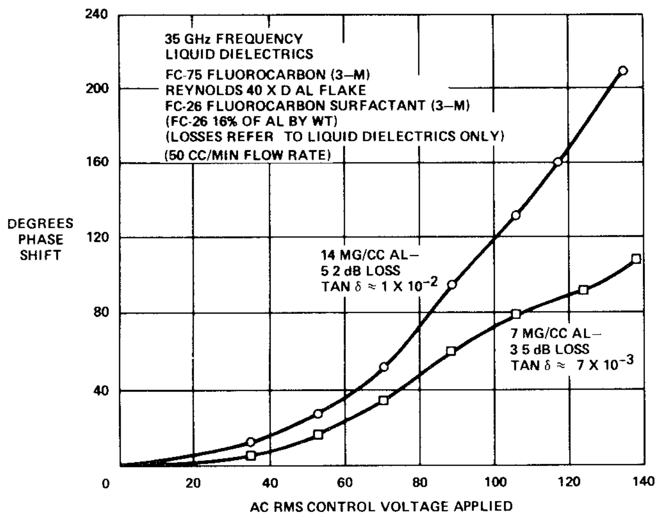

Fig. 5. Phase shift versus applied voltage, single-electrode WR-28 cell 8.9 cm long.

data in Fig. 5 are for a much more inert system based on a 3M Corporation "Fluorinert" liquid sold as FC-75. Even though it has a higher loss tangent than many hydrocarbons, it is neither flammable nor toxic, and allows good dispersion with proper surfactants. It is not known why it was less than half as sensitive to control fields as the n-heptane media, and yet showed lower loss for equivalent aluminum concentrations.

Data at 95 GHz were taken using a WR-10 waveguide cell, similar to that shown in Fig. 2. The liquid-filled section was 3.81 cm long, and the central electrode was 3.71 cm long, 2.03 mm wide, and 0.08 mm thick. The electrode supports were 0.38-mm thick Teflon. The end seals, impedance matching wedges, and liquid filling holes were scaled versions of those used for the WR-28, all described earlier. Liquid temperature was again 30°C, but flow rate through the rather small cross-section cell was proportionately reduced and better controlled to quantify flow-induced particle alignment effects discussed below.

The complete WR-10 waveguide cell had a (filled) VSWR of less than 1.3:1 and combined leakage and

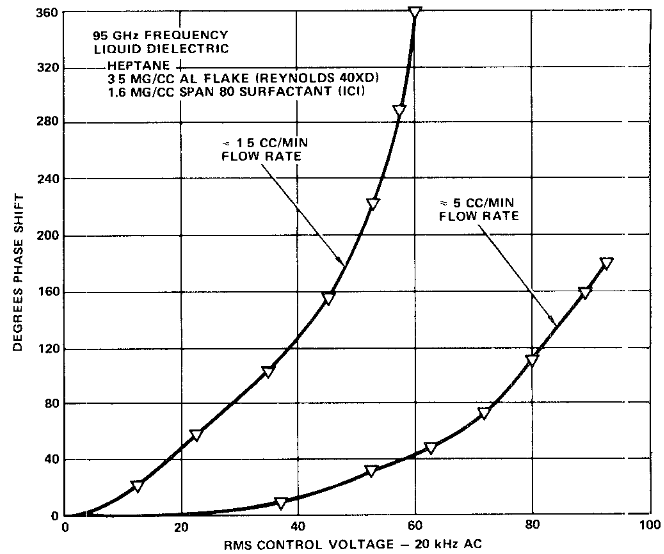

Fig. 6. Phase shift versus applied voltage, single-electrode WR-10 cell 3.81 cm long.

conduction loss of less than 1.2 dB. The same quantities (phase shift and loss) were observed at 95 GHz as at 35 GHz, using the same standard techniques.

Fig. 6 shows phase shift through the cell at 95 GHz versus applied voltage for a CLAD material similar to one described in Fig. 4. Data are presented for two flow rates to show the reduction in Kerr constant with increasing flow rate. This phenomenon was also observed in the WR-28 cell described earlier, but in that case the Kerr constant was nearly independent of flow rate above about 1 cm^3/s. It is thought that liquid flow in the WR-10 cell was less turbulent and at generally higher velocity than in the larger cell, thus providing a greater degree of flow-induced pre-alignment of the metallic particles in the CLAD medium.

Loss in the CLAD medium itself was less than 1.8 dB at 95 GHz for all control voltages applied, suggesting that with careful attention to cell tolerances, a 360° phase shifter could be built with less than 2-dB total loss using even this simply prepared liquid.

It has been found that losses in CLAD media are critically dependent on the concentration of residual ionic contaminants, such as the stearic acid anti-oxidant present in nearly all commercial aluminum powders. In order to remove most of this contaminant, the aluminum used to prepare the above media was washed and centrifuged out six times in clean heptane before use. Residual contamination was not, however, completely eliminated by this procedure, and it is expected that millimeter-wave losses could be further reduced by more careful liquid preparation.

No attempt was made to measure response or relaxation times for the above CLAD media; they are both expected to be long since no special care was taken to separate only the smallest aluminum particles from the broad range of sizes present in the commercial pigment. It has been shown that the response time of Kerr suspension

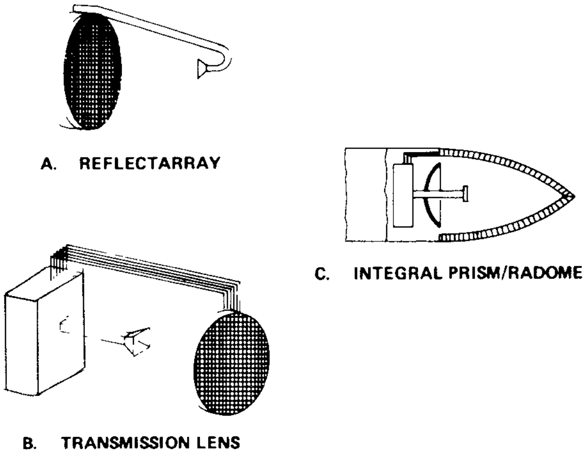

Fig. 7. CLAD lens implementations (from U.S. Patent 3 361 501).

decreases as the cube of the particle diameters and is also a sensitive function of the control voltage pulse leading edge amplitude [7]. The relaxation time after removal of the control voltage is also strongly dependent on particle diameter and on whether a "reset" field pulse is applied orthogonal to the control field.

IV. Applications

Perhaps the single most promising millimeter-wave application of CLAD media is in electronic-scanning antennas. Electrically variable permittivity media allow construction of variable-geometry lenses and prisms capable of focusing and deflecting energy from radiating apertures. Some implementations of this concept are shown in Fig. 7. The beam-steering lenses are essentially hollow dielectric tanks filled with CLAD media. Inside the lens is a dielectric egg-crate support structure carrying many parallel printed metal control electrodes arranged to form path-delay control cells.

The electrical thickness of the lens can thus be changed so as to provide a uniform phase taper across the aperture for beam deflection, or in any other way desired. If the lens is physically shaped to provide focusing power at zero control field, or if a conventional array or reflector forms the beam prior to the lens, it is possible to build internal resistive voltage dividers between the lens cells and thereby control beam deflection with only two external voltages. This could provide a millimeter-wave antenna with "x" and "y" beam stearing about as easily controllable as the beam position in a CRT. Conformal designs are also possible, as shown in Fig. 7.

While slightly less attractive than integrated techniques in the millimeter region, discrete waveguide cell CLAD arrays are feasible and have been demonstrated at *Ku*-band with components similar to the device shown in Fig. 2 [3].

V. Summary

The use of variable-permittivity media is a possible approach to reducing cost and improving performance of many microwave and millimeter-wave components. Applications in electric field controlled power dividers, switches, resonant cavities, and especially antennas suggest themselves. Considerable work remains to be done before liquid dielectrics are developed with the stability of solid-state devices, but fairly straightforward development techniques are available. Data on candidate CLAD media at 35 and 95 GHz and the possibility of losses decreasing in the higher millimeter bands provide encouragement that further work in this area will be especially fruitful. It would appear that the number of useful CLAD media, both metallic suspension and macromolecular solution types, is enormous, and that only a very few have been explored.

Acknowledgment

The author wishes to express his gratitude to Dr. M. Pike of the Commercial Chemical Division of 3M Corporation for suggesting and supplying the fluorocarbon surfactants used to prevent agglomeration in the FC-75-based CLAD medium. The author also wishes to thank T. G. Hame, now of General Dynamics/Pomona Division, for sponsoring the original work on CLAD media.

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