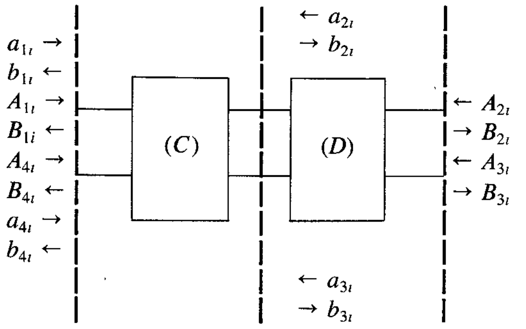
APPENDIX

A coupling segment of length ds can be represented by



where

$$\begin{aligned} a_{1t} &= A_{1t} & B_{2t} &= e^{-j\beta_d(dz-ds)} b_{2t} \\ b_{1i} &= B_{1i} & A_{2i} &= e^{j\beta_d(dz-ds)} a_{2t} \\ a_{4t} &= A_{4i} & B_{3i} &= e^{j(\beta_d-\beta_c)ds} b_{3t} \\ b_{4t} &= B_{4t} & A_{3t} &= e^{-j(\beta_d-\beta_c)ds} a_{3i} \end{aligned}$$

with

$$ds = R_e \, d\vartheta$$

$$\begin{aligned} dz(\vartheta) = {} & r(\vartheta + d\vartheta)(1 - \cos(\vartheta + d\vartheta)) \\ & + R_e(\sin(\vartheta + d\vartheta) - \sin\vartheta) - r(\vartheta)(1 - \cos\vartheta) \end{aligned}$$

β_d: phase constant of the straight guide

β_c: phase constant of the curved guide

By setting:

$$(B)_t = (S')_t (A)_i$$

$(S')_t$ can be derived:

$$(S)_i' = \begin{Bmatrix} 0 & S_{21t} e^{-j\beta d(dz-ds)} & S_{31t} e^{j(\beta_d-\beta_c)ds} & 0 \\ S_{21t} e^{-j\beta d(dz-ds)} & 0 & 0 & S_{31t} e^{-j\beta_d(dz-ds)} \\ S_{31t} e^{j(\beta_d-\beta_c)ds} & 0 & 0 & S_{21i} e^{j(\beta_d-\beta_c)ds} \\ 0 & S_{31t} e^{-j\beta_d(dz-ds)} & S_{21t} e^{j(\beta_d-\beta_c)ds} & 0 \end{Bmatrix}.$$

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Microwave Reflection at an Active Surface Imbedded with Fast-ion Conductors

Perambur S. Neelakanta, Jorge Abello, and Chaoli Gu

***Abstract*—The microwave reflection characteristics at a surface of a composite medium comprised of thermally controllable, solid-electrolyte based active-zones are studied. These zones are energized (heated) reconfigurably so as to alter their electric conductivity, and hence their reflection/transmission characteristics. Experimental studies at *X*-band frequencies on a test active surface formed by a two dimensional array of AgI pellets (fast-ion conductors) imbedded in a dielectric medium are presented. Suitability of the proposed composite-medium for broadband applications is indicated.**

I. INTRODUCTION

Controllable electromagnetic absorption and/or reflection by materials are of importance in the development of radar absorbing surfaces and in certain EMI/EMC problems. Conventionally, microwave materials composed by a combination of metallic and/or nonmetallic (dielectric) absorbing constitutents are used for this purpose. For discrete-tuned frequency applications magnetically and dielectrically lossy materials could be blended to obtain moderate performance on absorption/reflection characteristics. The base materials for such applications include: graphite/iron/aluminum particles (spherical/fibrous/flaky) dispersed in a host medium such as natural rubber-latex, polyisoprene, neoprene, silicone, urethene, etc. However, for better absorption the frequency-tuning is done by the principle of quarter-wave window(s) via multiple layers of lossy dielectrics.

An alternative approach suggested by Meyer *et al.* [1] consists of distributing a large number of magnetic dipoles on a conducting surface to achieve pronounced reflection/absorption characteristics depending on the orientation and distribution of the dipoles. A successful application of this principle has been reported by Chatterjee *et al.* [2]. Typically, a reflectivity reduction in the order of −20 to −30 dB could be accomplished at selective resonance frequencies

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by these passive surfaces. Uses of such single-frequency tuned-absorbers include narrow band RCS reduction, minimizing unwanted reflections inside aircraft radomes and reducing reflections from ship-borne structures, etc.

Modified versions known as graded absorbers designed for broadband applications have also been developed for the purpose of broad-band RCS reduction, EMI shielding, sidelobe absorption in antennas and as test screens used to prevent personnel radiation hazards in high power radar range applications.

The aforesaid materials are, in general, known as passive absorbers. In contrast, recently a class of electromagnetic materials/surfaces have been studied which can be manipulated electrically/electronically to alter their reflection characteristics, scattering pattern and frequency selectiveness. Such materials are known as active media with the surface made 'actively' sensitive to incident microwaves. The design principle of such surfaces is the logical extension of smearing the surface with the dipoles (as described by Meyer *et al.* [1] and Chatterjee *et al.* [2] except that the included dipoles at the resonant structures should be made electronically "active" or "tunable" so as to yield desired reflection/absorption characteristics. One such composite active surface has been described by Dempsey and Bevensee [3] who developed a matrix of thin conductive line segments joined (synapsed) at nodes with photoconducting cells which can be switched on by optical energy alone. Depending on the nodes swtiched (via electro-optical methods), the reflection from the surface could be configured to a desired pattern.

Presently, the use of pyrosensitive solid-electrolytes (such as AgI) are suggested as active elements at the nodes of the synaptic arrangement. On thermally energizing these nodes that solid-electrolyte material would exhibit superionic electric conduction at elevated temperature(s). With the result the surface (at the nodal points) which is dielectic at cold conditions becomes conducting under hot conditions. Thus, the microwave reflection at this test surface can be effectively altered by the electrothermal synergism. The heating of the nodes can be performed by conductive line segments of heating elements joined (synapsed) at the nodes where the solid-electrolytes are planted.

II. Physical Description of the Test Surface

To demonstrate the feasibility of realizing an active surface of the type under discussion, a test surface shown in Fig. 1 was constructed. It consists of a heat resistant dielectric such as ceramic plate with two-dimensional array of holes made to accommodate the pellets of a solid-electrolyte. There are a number of solid-electrolytes which exhibit high electric conductivity (of the order of 10^{-1} to 10^{-4} S/cm) at characteristic temperatures. For example, $RbAg_4I_5$ has a high conductivity (.27 S/cm) even at room temperature; other materials like β-alumina and β-AgI show increasing conductivity with increasing temperature. The compound β-AgI exhibits superionic conductivity with an abrupt transition at a temperature close to 147°C. This transition is known as the β to α—transition and the family of materials which exhibit this phenomenon are described in [4].

In the construction of the active test surface of Fig. 1, silver iodide (AgI) powder was pelleted as tables and used in the nodes of the ceramic plate. These nodal points were connected by constantan wire on the rear side of the ceramic plate. By properly energizing the matrix of heating elements from a direct current source, the solid-electrolyte pellets in the two-dimensional array could be chosen for heating selectively.

Upon energization those pellets which receive the heat energy would switch to α-phase posing thereby high conductivity zones. When microwave energy falls on these zones would therefore suffer intense reflection. Hence, with the proper choice of nodes selected for heating, the reflection/transmission pattern of the overall surface can be controlled and configured as desired.

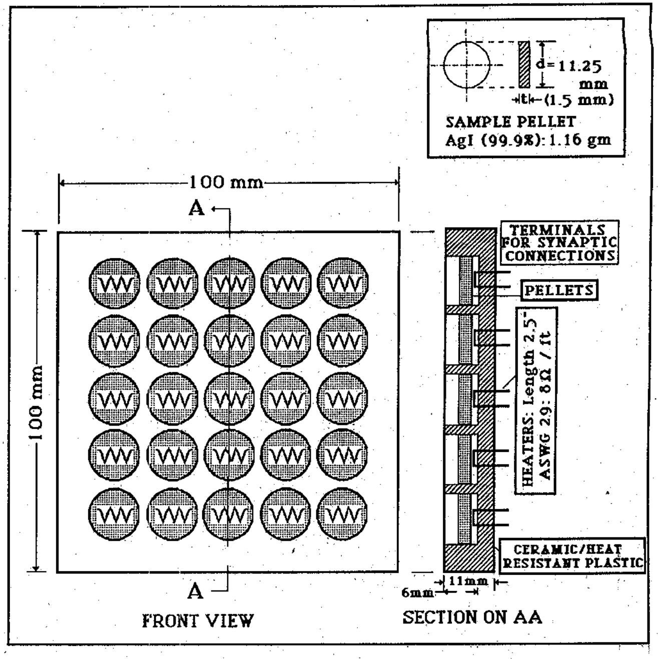

Fig. 1. Test active surface.

III. Test Results and Discussion

The test surface illustrated in Fig. 1 was irradiated by a monostatic microwave (X-band) transmitter/receiver arrangement shown in Fig. 2. The wave normally incident on the test surface is reflected and detected by the arrangement of Fig. 2 and the detected output proportional to the reflected energy is monitored at the SWR meter and recorded on a plotter.

In the experiments conducted, the nodes in the middle region of the surface were chosen and heated by a direct current passing through the interconnected filaments. The temperature at one of the nodes was monitored by a miniature thermometer. Shown is Fig. 3 is the change in the microwave reflectivity at 9.4 GHz as the AgI pellets were heated. Also depicted in Fig. 3 is the way the surface reflectivity returns to its original value when heating was terminated. The experiment was repeated at other spot frequencies over the X-band, namely, 8.3 GHz, 8.9 GHz, 9.9 GHz, 10.6 GHz and 11.5 GHz. The corresponding reflectivity characteristics observed were almost similar to that of Fig. 3. From the results of Fig. 3, the following can be inferred:

1) The solid-electrolytes (fast-ion conductors) are feasible candidates for inclusion as active elements in the development of microwave active surfaces.

2) Although β-AgI was used here as the test (active) element, there are other superionic materials which can be used for the same purpose at lower temperature operations [5], [6].

3) Similar to the optically-triggered synaptic array proposed by Dempsey and Bevensee [3], it is also possible to use solid-electrolytes to realize reconfigurable arrays.

4) The use of solid-electrolytes as pellets in the composite surface does not warrant any special or sophisticated material integration technolgy.

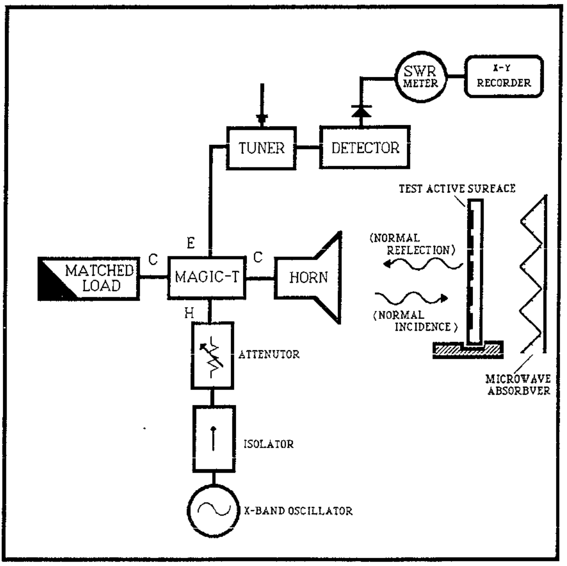

Fig. 2. Measurement of reflectivity of the test active surface at X-band frequencies.

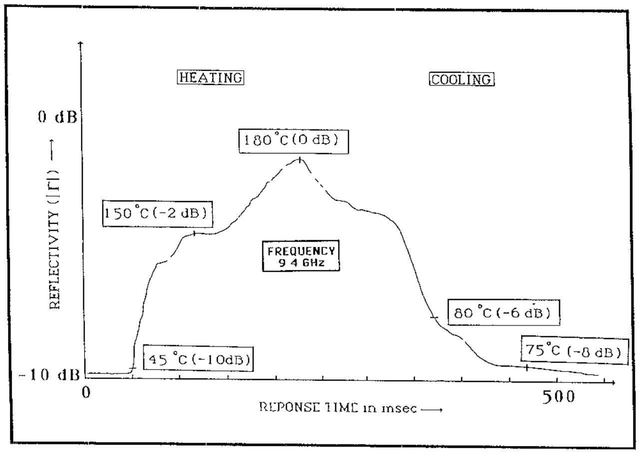

Fig. 3. Temperature dependent reflectivity of a 25 × 25 pellet array: heating and cooling.

5) Further, the solid-electrolytes permit their use in bulk form which simplifies active surface fabrication. The size and shape of the pellets can be conveniently chosen to match the overall reflecting surface geometry.

6) Energization of the solid-electrolyte nodes to achieve the reflectivity switching is simple inasmuch as it involves current injection through the filament which can be accomplished by simple electronic circuits.

7) The proposed active surface can be used in conjunction with quarterwave windows and/or graded dielectric media to realize tuned and/or broad-band frequency responses. It is indicated by one of the authors (with others) elsewhere [7] that the conductivity of the material like AgI in the α-phase is invariant with the frequency of the incident microwave energy. That is, the results presented in [7] indicated that the electrical conductivity of β-AgI measured over X-band frequencies (8–12 GHz) does not change significantly in the α-phase; and, the measured dielectric property (permittivity) of β-AgI (in β-phase) also remained frequency-invariant. These again are confirmed in the present studies by the observation that microwave reflectivity characteristics measured at several spot frequencies mentioned earlier do not vary appreciably. This indicates the suitability of such materials for broad-band applications.

Further, though the present study refers only to normal incidence, the following may be surmised with regard to the oblique incidence and wave polarization at the test surface: The active medium described here, which becomes α-phase (under energization), is almost similar to an artificial dielectric [9] composed of an array of conducting inclusions in a host-dielectric. The dielectric property (and hence the reflectivity) of the test medium would therefore correspond to those of an artificial dielectric. Such properties are known to be almost frequency independent [9] provided the dimensions and spacing of the inclusions are small in comparison to wavelength; and, reflectivity for both normal as well as oblique incidence is decided by simple air-to-dielectric boundary conditions. No polarization changes would therefore be anticipated. However, if the medium is made inhomogeneous and/or anisotropic, polarization rotation is feasible [9], [10]. A method of realizing such an active medium is to make the active ingredients helical or spiral shaped so that, upon energization, they become conducting chirals; and, the medium could then effectively induce (left- or right-handed) polarization (rotation) in the interacting electromagnetic wave.

8) To economize the use of pure solid-electrolyte a mixture of solid-electrolyte plus an inactive ingredient (like graphite) can be use in lieu of the solid-electrolyte itself [7].

IV. CONCLUSION

The present study is the first-level effort which indicates the feasibility of adopting solid-electrolytes in the development of active surfaces exhibiting controllable microwave reflection characteristics with configurable patterns and broad-band application potentials. Design optimization of the proposed strategy is in progress [8], and, the plausible ways of realizing a chiralic active medium using solid-eletrolytes are under consideration.

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