Millimeter Wave Measurement of the TM Mode Cutoff for EBG Structures Fabricated in LTCC for Antenna Applications

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***Abstract*—This paper presents characterization of low temperature co-fired ceramic (LTCC) based electromagnetic bandgap (EBG) structures, and a test method to measure the TM mode cutoff frequency at millimeter wave frequencies. This test method differs from prior art in that the TM mode surface wave launchers are fabricated in the same LTCC module as the EBG structure under test to realize a compact and repeatable test vehicle. A pair of two port transmission measurements will experimentally yield the TM mode cutoff frequency. This frequency defines the lower bound for the surface wave bandgap. The TM mode cutoff frequency is a very important parameter where EBG structures are integrated into millimeterwave LTCC antennas because this cutoff frequency must be lower than the antenna's operational frequency range. This proposed test method may be used with any open EBG structure which exhibits a TM mode cutoff frequency.**

I. INTRODUCTION

Low temperature co-fired ceramic (LTCC) is an attractive substrate technology for millimeterwave antennas because it accommodates multiple dielectric and metal layers. One of the major issues with millimeterwave LTCC antennas is the excitation of parasitic surface waves by the antenna elements, vias, transitions, and other features especially for substrate materials with relative permittivity >4. Surface waves can severely distort antenna patterns, lower antenna gain, and therefore surface wave suppression is a critical design goal. One means of suppression is to fabricate an electromagnetic bandgap (EBG) structure into the LTCC substrate. A prominent example is the Sievenpiper high-impedance surface [1], [2], sometimes called a mushroom structure.

The surface wave bandgap can be designed using analytic tools, but experimental verification of the band edges is highly desired to confirm proper operation. The lower edge of the bandgap for the Sievenpiper EBG structure is a TM mode cutoff frequency. This paper presents an experimental procedure that can be used to directly measure the TM mode cutoff at millimeterwave frequencies up to at least 100 GHz.

Measurement of the TM mode cutoff for a Sievenpiper EBG structures have been routinely performed at microwave frequencies up to 10 GHz using coaxial probes [1], [2] or broadband linearly polarized test horns [3]. At millimeter wave frequencies of 60 GHz to 100 GHz, the physical placement of test horns and coaxial probes with respect to the test structure becomes much more challenging due to small dimensions. It then becomes attractive to integrate the surface wave launchers into the same substrate hosting the EBG structure.

The following test method is described using DuPont 9K7 Greentape™. This LTCC material was used because of its very low loss tangent at millimeterwave frequencies (tan $\delta = .0012$ at 60 GHz) and its high degree of dimensional stability after the initial firing. It is also available in a nominal 5 mil thickness which is convenient for implementation of 60 GHz and 77 GHz EBG structures.

II. TM SURFACE WAVE LAUNCHER

Two surface wave launchers are fabricated with the EBG test structure. The design is shown below in Fig. 1 where a microstripline transitions into a horn. The LTCC test structure is 5 tape layers thick but only the top three layers are used for the EBG structure and TM mode launchers, which share a common ground plane between tape layers 2 and 3.

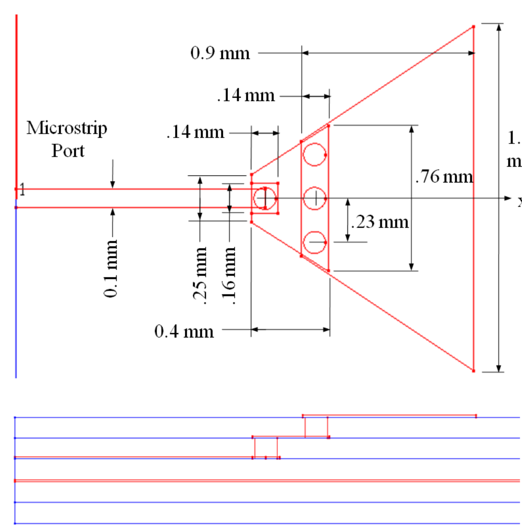

Fig. 1. Surface wave launcher; plan and elevation views.

III. EXAMPLE OF THE EXPERIMENTAL METHOD

A 60 GHz Sievenpiper EBG structure was designed using effective media models [4] and transverse resonance equations to analytically predict the surface wave bandgap. The TM mode cutoff is predicted to be 53.1 GHz and the bandgap extends up to the TE mode cutoff near 78 GHz. This EBG structure uses 3 layers of 108 um thick DuPont 9K7 tape above its ground plane, and it has a single layer of 305 um square patches spaced one tape layer away from the ground plane. The square lattice has a 381 um period, and vias of diameter 116 um. These are all post-fired dimensions. Fig. 2 shows a 3D perspective view of the buried metal in the TM mode test vehicle where the top 3 tape layers are hidden from view.

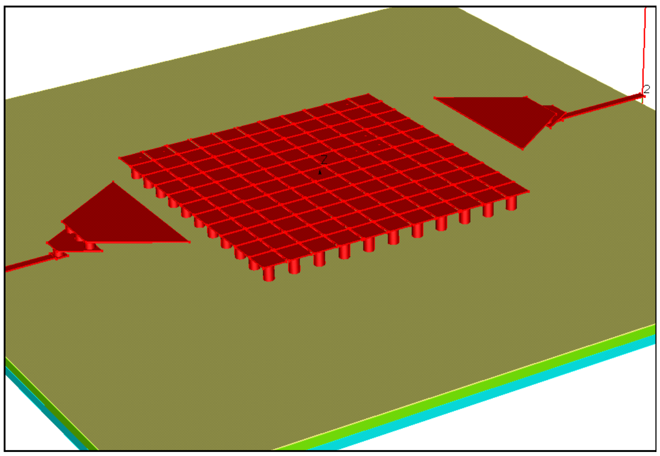

Fig. 2. 3D view of a two-port TM mode test structure.

The TM mode test structure shown in Fig 2 is a two-port network. The LTCC test vehicle is wafer probed using 150 um GSG probes. Local cavities allow the probes to reach down through two tape layers to connect to 50Ω microstrip lines. A similar test vehicle containing the same size ground plane and identical TM mode launchers, but without the EBG structure, is used for a calibration measurement. The test procedure involves making a scalar two port measurement of insertion loss for the test vehicle with the EBG structure, and then repeating that measurement for a similar test vehicle without the EBG structure (patches and vias) for calibration. The difference (in dB) between these two measurements yields a normalized coupling plot for TM mode surface waves traveling through the LTCC EBG structure.

An example normalized coupling plot is shown in Fig. 3. This plot is actually made with insertion loss data from two full-wave simulations generated by CST Microstripes 2012. Coupling is near zero dB at frequencies far below the bandgap because the TM mode is not tightly coupled to the EBG structure. As frequency increases, the coupling rises because the TM mode is being guided by the EBG structure. Coupling peaks and then falls rapidly with frequency as the bandgap or stopband is realized. The TM mode cutoff is defined as the zero crossing of this normalize coupling plot, which in this case is near 55.9 GHz. The transverse resonance model predicted 53.1 GHz.

This TM mode measurement technique is being demonstrated with 60 GHz and 77 GHz Sievenpiper EBG structures. Critical dimensions such as gaps between EBG patches are fabricated using laser ablation. Experimental results will be shown at the conference. It should be appreciated that any type of LTCC EBG structure exhibiting a TM mode cutoff at millimeter wave frequencies can be characterized with this measurement technique.

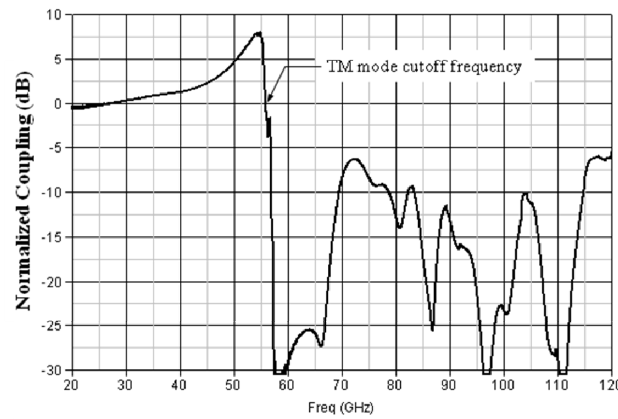

Fig. 3. Example of a normalized coupling plot for the TM mode surface wave. The zero crossing identifies the TM mode cutoff frequency for the EBG structure under test.

IV. CONCLUSIONS

We have presented a test method to measure the TM mode cutoff frequency of a Sievenpiper EBG structure at millimeter wave frequencies. In this method, the EBG structure and surface wave mode launchers are fabricated together in the same low temperature co-fired ceramic (LTCC) package. A pair of two port insertion loss measurements are performed using conventional GSG wafer probes to create a normalized coupling plot. A numerical example is shown here for a 60 GHz EBG structure. Measured data on 60 GHz and 77 GHz EBG structures will be presented at the conference.

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