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Integrated Waveguide Slot Antenna and Cavity Filter Using Hollow SIW in LTCC Technology

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Abstract — A hollow substrate integrated waveguide (HSIW) is proposed to realize low-loss millimetre-wave (mm-wave) transmission lines. A 38 GHz waveguide slot antenna integrated with a cavity bandpass filter is fabricated in LTCC to demonstrate the HSIW potential. The measured radiation pattern of the waveguide matches well with the simulations. The HSIW medium has great potential for further development and could be used to realize integrated passive elements such as filters, slot antennas and power combiners for future communications needs.

Index Terms — Ceramics, waveguides, SIW, multichip module, microwave circuits.

I. INTRODUCTION

Increased use of the millimeter-wave frequency range is an important potential solution to spectrum congestion. To meet the demand for low cost transceivers, particularly for high data rate wireless communications and automotive radar sensors, both silicon and compound semiconductor integrated circuit (IC) technologies are immensely important. There is a need for system-in-package or system-on-substrate technology that can be integrated these ICs with low-loss passive components such as resonators, filters, power combiners and antennas. Among the various transmission lines, rectangular waveguide (RWG) still offers an excellent solution at these frequencies due to its lower loss [1]. Substrate integrated waveguide (SIW), a dielectric-filled waveguide formed in a substrate, is interesting as it can be fabricated using PCB or LTCC technology, and can dramatically reduce the cost of millimeter-wave systems [2-3]. LTCC is especially interesting due to its thermal and mechanical properties [4-5] and also resistors, capacitors and inductors can be embedded, instead of using additional surface mount technology (SMT) components, potentially leading to very small transceiver modules.

The conventional SIW is normally based on a solid dielectric substrate with two parallel rows of metallic posts (vias) used to replace the sidewall of a traditional RWG. For lower loss, and in antenna applications, it is desirable to integrate an air-filled waveguide into the substrate [6]. However, this presents substantial fabrication challenges, such as the requirement to metalize the walls. But by retaining the use of via-hole sidewalls and introducing a hollow cavity with the upper and lower supporting layer metallization, considerably lower loss is expected. By incorporating this hollow cavity, the following advantages are expected:

1) Lower loss due to the removal of most of the dielectric
2) More suitable for high permittivity substrates and higher frequencies, where the size of SIW otherwise tends to be too small to accommodate the vias.
3) The waveguide can be directly connected with normal RWGs, whereas the conventional SIW requires more complicated transitions with potentially more loss.
4) An air-filled guide is advantageous for the design of many antennas.

Although HSIWs have significant advantages, there are major LTCC process challenges that need to be addressed to realize them. In particular, hollow cavities are seriously deformed in the lamination and co-firing stages of the standard LTCC process recommended by the green tape supplier. A sacrificial layer may be used to support the upper and bottom layers of the channels/cavities during these stages. However, they still undergo large deformation and it is very difficult to completely prevent the residual deformation of the cavities/channels, even if the lamination conditions are carefully optimized [7].

This paper presents a technique for realizing this novel hollow SIW (HSIW) by applying a novel multi-stage lamination process. The aim is to establish a technology that could realize the advantages of HSIWs mentioned above while employing as many LTCC standard process steps as possible. This is achieved by employing top and bottom broadwalls on dielectric layers suspended above and below the cavity, as shown in Fig. 1.

To demonstrate the potential of the HSIW, integrated passive elements such as filters and antennas are investigated. For filters, direct-coupled cavity waveguide filters are chosen for the advantage in small size and high performance. A design procedure for cavity waveguide filters that is reliable for bandwidths up to 20 percent has been reported by Cohn [8]. We also investigate slot antennas in order to explore the advantages of HSIW for the design of antennas and possible integration with components such as resonators and power combiners for future communication needs.

II. DESIGN

A. HSIW

The HSIW can be view as a normal partially-filled RWG with its inside walls replaced by two rows of metallic posts as illustrated in Fig. 1. The theoretical analysis of HSIW could be performed by combining both structures. For a partially-filled RWG which is represented as a two-dielectric symmetrically-loaded RWG, the characteristic equations can be derived from Maxwell's equations constrained by boundary conditions [1].

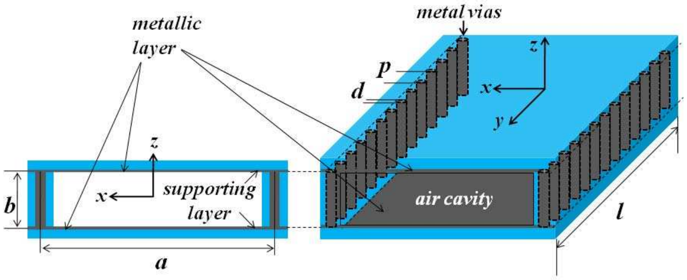

Fig. 1: Illustration of cross section and 3D view with metallization inside the hollow SIW.

According to the SIW analysis in [9] and from modeling using HFSS, the design parameters of a=7.26 mm, b=1.0 mm, d=0.30mm and p=0.60 mm were found [10].

B. Waveguide Slot Antenna and Cavity Filter

Based on S. B. Cohn, the waveguide cavity and its equivalent circuit may represented by the π network shunted with inductive susceptances at each end, as shown in Fig. 2. The two shunt susceptances $\overline{B}$ could be neglected as compared to $\overline{B_k}$ which is the dominant element. The electrical length, θ_k, on the other hand, is nearly equal to π. The series reactance, $\overline{X}$ is used as the series resonant circuit in the prototype filter.

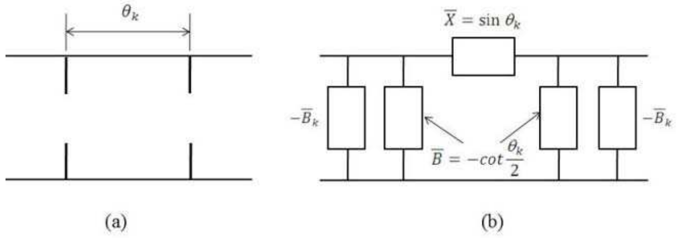

Fig. 2: A waveguide cavity and its equivalent circuit [8].

Impedance inverters could be realized as the shunt inductive reactance and two equivalent transmission lines as shown in Fig. 3 [8]. The dimension of a 3-iris waveguide separated by spacing l_k is illustrated in Fig. 4.

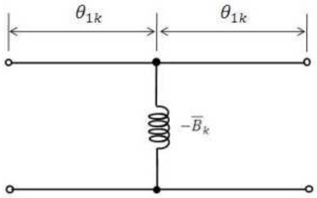

Fig. 3: The impedance inverter.

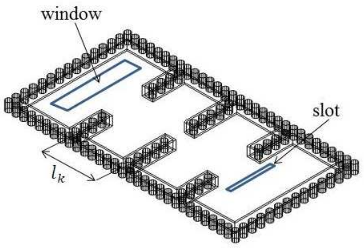

Fig. 4: Illustration of cavity filter with a slot antenna.

Before that, the bandpass filter configuration needs to be initially determined. As the impedance inverters are absorbed as part of the cavity length, the physical length of the k-th cavity becomes (1). Thus, the length of the k-th cavity at β=β_0 given by (2).

$$l_k = \frac{\lambda_{g0}}{2} + \frac{\lambda_{g0}}{2\pi}(\theta_{1k} + \theta_{1k+1}) \tag{1}$$

$$l_k = \frac{\lambda_{g0}}{2} + \frac{\lambda_{g0}}{4\pi}\left(arctan\frac{2}{\overline{B}_{k+1}} + arctan\frac{2}{\overline{B}_k}\right) \tag{2}$$

A single slot antenna that exhibits linear polarization and low sidelobes was then modeled to fit the dimension of the cavity filter, using the method of A. Farrall and P. Young to model the slot antenna [11].

III. FABRICATION AND MEASUREMENT

The 9K7 tape system of DuPont was chosen as it is suitable for frequencies up to 100 GHz and beyond [12] with dielectric constant, ε_r of 7.1, loss tangent of 0.0010 at 10 GHz and specified DC conductivity of 3.7x10^7 S/m for Ag conductor. The supporting layers of the waveguide were via punched and cut using a Nd:YAG laser machine (ProtoLaser 200 from LPKF$^{\text{TM}}$) before being stacked and laminated at 20 MPa, 70 °C for 10 min, to provide sufficient densification. The top and bottom layers were pressed separately with the same conditions. Then, LL601 paste for via filling and LL612 paste for conducting layer were deposited with an Aurel VS1520A screen printer. All layers were then aligned using a jig and laminated again with a uni-axial laminator under conditions of 2 MPa, 70 °C for 5 min. The stacked green state tapes were then co-fired for 26.5 hours by using a programmable furnace according to the appropriate temperature profile.

The feed into the hollow SIW was realized with a window cut in the bottom supporting layer to match with the dimensions of the standard WR28 waveguide flange. Three pairs with different waveguide lengths were used and a multimode calibration technique was employed [13-14].

IV. RESULTS

Fig. 5 shows the modeled insertion loss and return loss of a hollow SIW with a length of 30 mm, confirming that very low loss can be expected from the RWG-like hollow SIW. Fig. 6 shows a photograph of the sample, part way through the fabrication process so that the internal detail is visible. The measured S_{11} of the waveguide cavity and filter is shown in Fig. 6. The measurement of the radiation pattern of the waveguide slot antenna and cavity filter was performed using a 67GHz PNA and a standard gain horn antenna placed inside an anechoic box. The measured radiation pattern is shown in Fig. 8. The plot shows both the *E*-plane and *H*-plane patterns, with a close fit with the modeled performance.

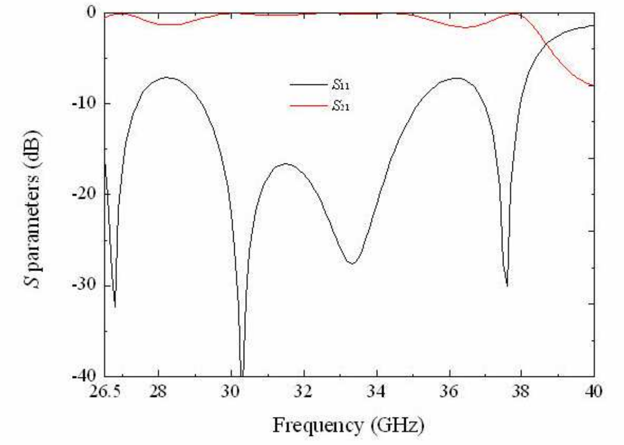

Fig. 5: The simulated insertion and return loss of the hollow SIW.

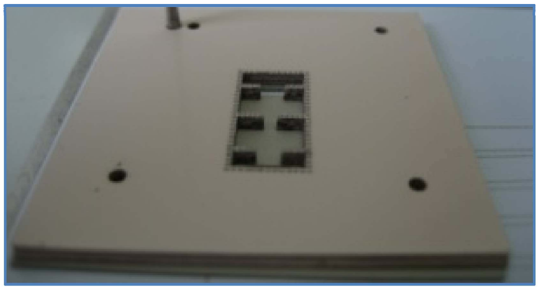

Fig. 6: Photograph of the fabricated HSIW structure prior to placement of the top layers.

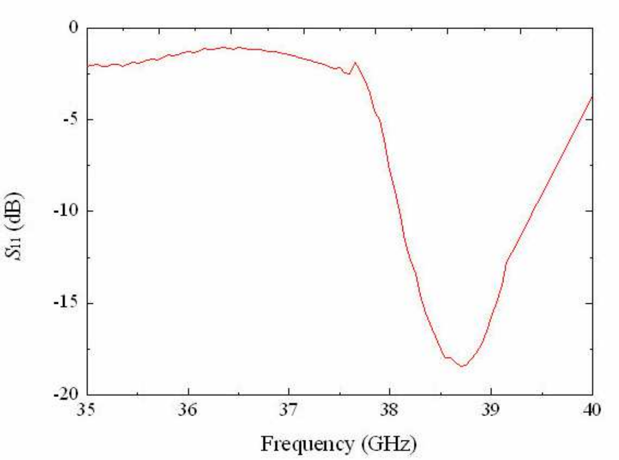

Fig. 7: Measured return loss of the integrated waveguide slot antenna and cavity filter.

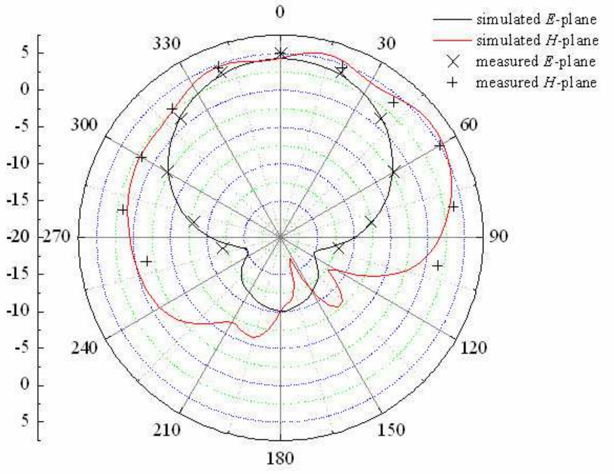

Fig. 8: Measured and simulated E-plane and H-plane radiation pattern of the slot antenna.

V. CONCLUSIONS

A 38 GHz direct-coupled cavity waveguide filter integrated with slot antenna has been successfully fabricated using hollow SIW in LTCC technology. The radiation pattern of the antenna matches well with the modeled one. The hollow SIW (HSIW) has potential for further development and could be used to realize integrated passive elements such as filters, slot antennas and power combiners that may support the next generation wireless communication technologies.

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