Substrate Integrated Slab Waveguide (SISW) for Wideband Microwave Applications

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***Abstract* — A new slab waveguide integrated in planar form has been developed for wideband microwave applications. The guide is synthesized on a substrate by adding air hole into an SIW (substrate integrated waveguide). Using these techniques, a substrate integrated slab waveguide (SISW) covering the X and Ku bands has been designed and measured. Wideband microstrip transitions are presented with S21 lower than 0.75 dB and S11 below –15 dB over the entire band. Propagation constant and quality factor measurements are also presented with a Q value of 308.**

I. INTRODUCTION

The slab waveguide is known for its wide bandwidth when designed with a high permittivity dielectric slab [1]. Using a permittivity of 5 for the slab, two conventional rectangular waveguide bands can be covered with one slab waveguide. This extended bandwidth can be useful to design frequency doublers or mixer, which may require wide bandwidth transmission line. However, like the rectangular waveguide, the integration of this guide with planar circuits requires a mechanical assembling. In the microwave range, the physical dimension of planar line and waveguide are quit different and some kind of tuning is usually necessary to achieve good matching. These procedures increase the cost of the overall systems.

In the last years, numerous articles have been presented on the Substrate Integrated Waveguide (SIW) [2]-[5]. This guide is synthesized directly on the substrate with arrays of metallic posts. It provides a cost effective solution to embed high quality factor components in the same substrate used for the planar circuits. It is then possible to implement waveguide components and planar circuits using the same process without any additional step.

The same technique can be used to embed a slab waveguide with planar substrate. In this case, arrays of air holes are added in the waveguide to synthesize (simulate) a lower permittivity region. This paper presents some fundamental properties of this waveguide. Different holes pattern are analyzed and measurement results for transitions, propagation constant and quality factor Q are presented for SISW guides covering two standard waveguide bands, the X and Ku band.

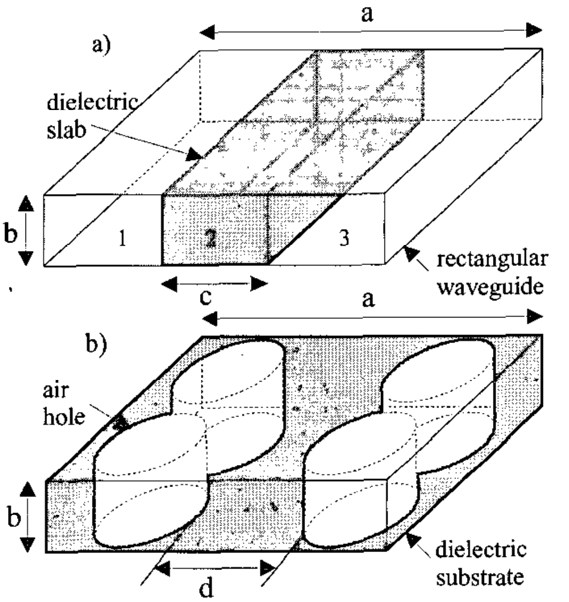

Fig. 1. a) Dielectric Slab Waveguide. b) Substrate Integrated Slab Waveguide.

II. SISW ANALYSIS

The dielectric slab waveguide is composed by a dielectric slab placed in the middle of a rectangular waveguide as illustrated in Fig. 1a). This slab uses a high permittivity substrate to increase the operating bandwidth. The field for the TE_{10} is thus more confined inside the dieletric lowering the cut-off frequency. In order to design an SISW, a lower permittivity must be synthesized in region 1 and 3. To do this, air hole are used to defined a region with an equivalent permittivity lower that the substrate, as illustrated in figure 1b). The slab waveguide bandwidth is related to the permittivity ratio between regions 1 and 2 and the slab thickness [1]. To increase the bandwidth, the electromagnetic field of the TE_{10} must be confined in the dielectric slab. It is thus important to analyze the hole pattern in order to get the lowest equivalent permittivity.

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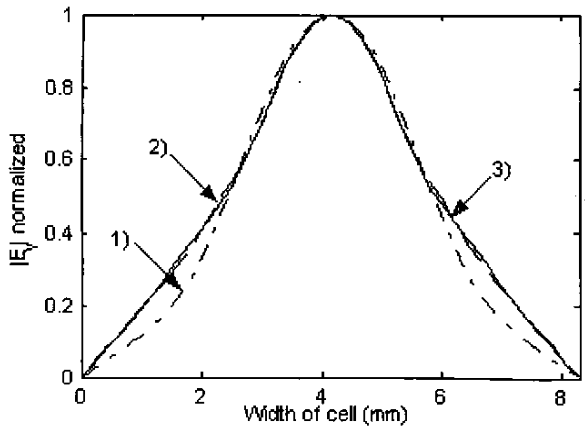

Fig. 2. Electric field distribution on the cross-section on the SISW at 25 GHz for three different structures: 1) 2 holes, 2) 4 holes, 3) 6 holes.

Using the same approach as presented in [6] the electromagnetic field distribution can be calculated for this structure. This has been done for three different structures changing the hole diameter. Only one period is simulated and the electric field distribution is found by applying the Floquet theorem to calculate the eigen values and eigen vectors.

The dimensions, referring to Fig. 1b), are: a = 8.3 mm, b = 0.635 mm, d = 1.8 mm and ε_r=10.2. The distance between two adjacent holes is fixed to 250 μm. This is the minimum distance between holes that can be processed in our research center. The structure 1 in Fig. 2 uses two holes with a radius of 1.5 mm, the structure 2 uses four holes with a radius of 0.6875 mm and the structure 3 uses six holes with a radius 0.42 mm. Fig. 2 shows the electric field distribution in the cross section of waveguide at 25 GHz. We can see that bigger holes provide better field confinement and consequently provide wider bandwidth. This is easily understandable since by using a bigger hole we remove more material in each cell. This results is less obvious when we compare smaller hole, like the structure 2) and 3). In these case the field distribution over the holes pattern is quasi-linear.

In order to obtain the lowest equivalent permittivity, the air area in each cell must thus be maximized. By removing more material the contrast between region 1 and 2 is higher. The field is then concentrate inside the region 2. The ratio air/cell area has been analyzed for different holes pattern. Results are shown in Fig. 3. All dimensions are normalized. The minimum distance between two adjacent holes has been kept constant. Using these results it is possible to find the most suitable pattern in order to maximize the air/cell ratio.

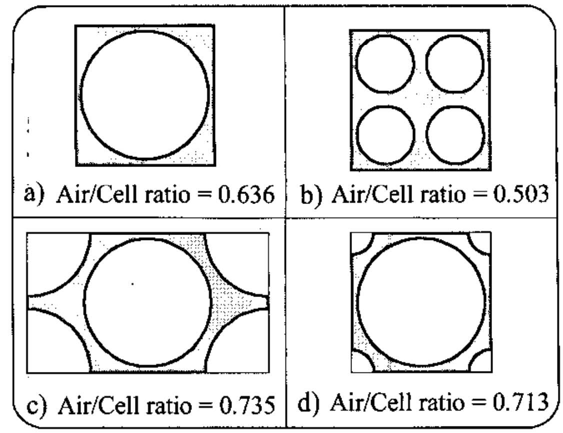

Fig. 3. Comparison of air/cell ratio for different pattern: a) rectangular pattern, b) rectangular pattern with small hole, c) triangular pattern, d) rectangular pattern with multiple size holes.

Comparison of Fig. 3 a) and b) shows that by using a rectangular pattern the air area is maximized by using a bigger hole. This explains why the field is more confined in the first structure of Fig. 2. Fig. 3 a) and c) show that for a fixed hole diameter, the triangular pattern provides a better air/cell area ratio that the rectangular pattern. However, all holes diameter are not always available in the manufacturing process and the fixed size of the waveguide is an additional constraint in the choice of the holes size. With all these constraints, another way to increase the air area is to use different holes diameter. Fig 3 d), compare to c), shows that by using different holes size, an air/cell area ratio close the triangular pattern can be obtained.

The slab waveguide is an enclosed structure. It has been stated that the sidewall can be removed without effect on the electromagnetic field if the dielectric contrast between region 1 and 2 and the frequency are high enough [1]. However, for a system design, it is not suitable to keep an open waveguide, which can cause crosstalk with other transmission lines. To close the waveguide, two arrays of metallic via are used. The spacing between via and their position are found using a method presented in [5].

II. MEASUREMENT RESULTS

With the technique presented in section II, an SISW covering the X and Ku band has been designed. The substrate used is the Rogers RT/Duroid 6010 with a thickness of 25 mil. Using this substrate the width of the microstrip of 50Ω is 0.6 mm. All the other dimensions are shown in Fig 4. Using the technique presented in [5] the cut-off frequency for the TE_{10} is found to be 7.3 GHz and 18.13 GHz for the TE_{20}. It is then possible to cover the X and Ku band with only one waveguide.

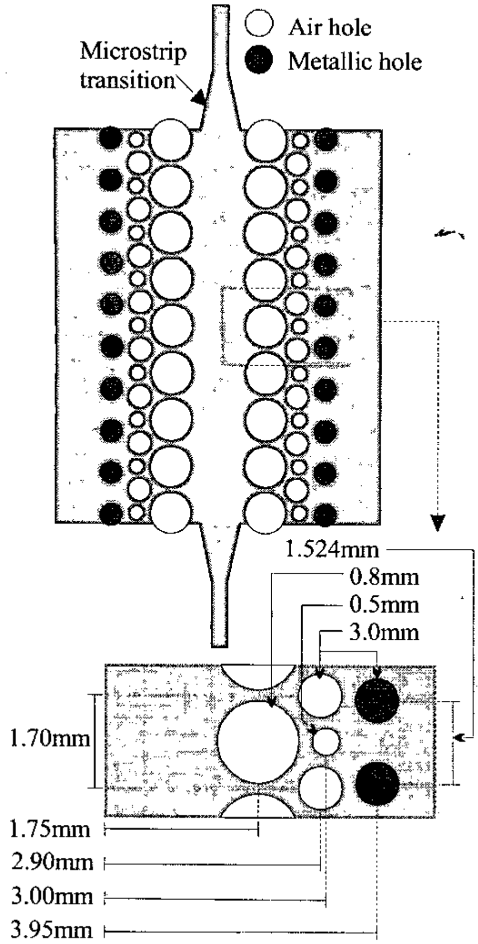

Fig. 4. Structure Measured: SISW realized with three different holes size and two microstrip transitions.

The manufacturing process of this waveguide is divided in three steps. First of all, an LPKF prototyping machine is used to drill the hole and grave the planar circuits. Secondly, a thin layer of copper is solder over the air hole on both sides of the substrate. Finally, the mechanical via arrays are added to form the waveguide sidewall. A TRL calibration is performed to remove the effect of the test fixture in the measurements.

A. Transitions from Microstrip to SISW

Transitions from planar circuits to the SISW are needed in order to integrate both structures together. Since the field distribution in the slab waveguide is similar to the one in the rectangular waveguide, the same transition structure presented in [2] can be implemented with the SISW. This transition provides a wide bandwidth and can be designed to cover all the SISW bandwidth.

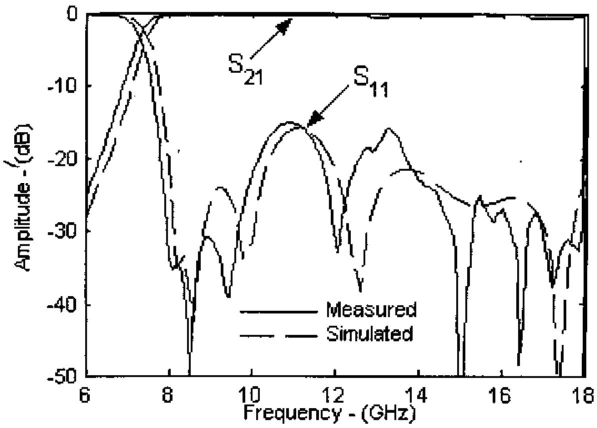

Fig. 5. Measured and Simulated Transition results.

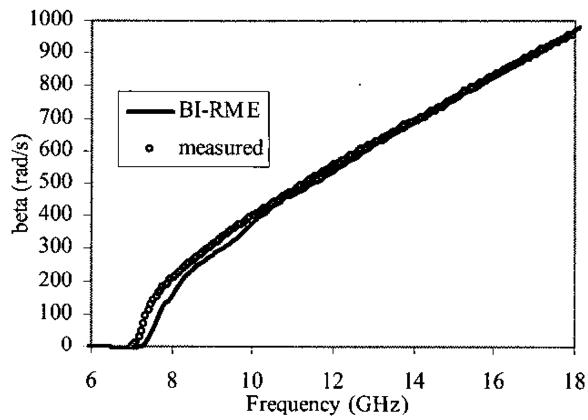

Fig. 6. Measured and Simulated Propagation results.

The transition is composed by a microstrip taper as illustrated in Fig. 4. The taper dimensions are optimized to minimize the reflection loss. To cover the waveguide bandwidth, from 8 to 18 GHz, the dimensions are: length=2.1mm and opening width=1.5mm. The simulated and measured results for a back-to-back transition are presented in Fig. 5. The S_{11} is lower than -15 dB from 8 to 18 GHz and the total insertion loss are better than 0.75 dB for the two transitions and an SISW of 14.4 mm.

B. Propagation constant

With two different lengths, the propagation constant can be evaluated using the same approach as presented in [5]. The simulated and measured results are presented in Fig. 6. Both results are in good agreement. With two lengths the losses can also be evaluated. However, the insertion loss for all the structure is all at the same level and the influence of the S_{11} is higher than that of the loss. Another way to characterize the loss is to measure the quality factor.

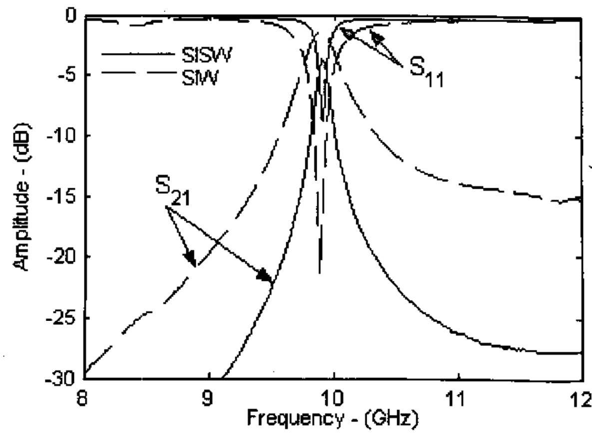

Fig. 7. Measured and Simulated results for the resonator: Comparison of the SIW and SISW.

C. Quality Factor

The measurement of the quality factor can be done using a single cavity as explained in [7]. The cavity is formed with two metallic posts placed in the middle of the waveguide and spaced by half a wavelength. The microstrip transition presented in section II a) is used to measure the SISW cavity, and a second transition is optimize to measured the SIW. The unloaded quality factor $Q_{unloaded}$, is calculated from the measurement using eq. (1) to (3).

$$Q_{loaded} = \frac{f_o}{\Delta f} \quad (1)$$

$$Q_{external} = 10^{-([S_{21}(dB)/20]} \cdot Q_{loaded} \quad (2)$$

$$Q_{unloaded}^{-1} = Q_{loaded}^{-1} - Q_{external}^{-1} \quad (3)$$

To cavities have been designed to resonate at 10 GHz. The first cavity is design using the SISW and the second using a SIW. The measured results are given in Fig. 7 for both structures. The unloaded Q-factor for the SISW is 308 compared to 332 for the SIW. Since the SISW contains air we can expect the quality factor would be higher than the SIW. However the thin layer of metal soldered on both side of the SISW adds some loss coming from a gap between the PCB and the metal plate.

V. CONCLUSION

The new Substrate Integrated Slab Waveguide (SISW) has been introduced. It is realized by placing air holes in a SIW. The main advantage of this new structure is a much wider operational bandwidth than the SIW. Several hole patterns have been studied. The triangular pattern was proved to produce the best field confinement. Using different hole sizes, composite pattern can also provides field confinement similar to the triangular pattern.

In order to excite the structure, broadband transitions were designed and used to measure the propagation constant and quality factor. Results show good agreements between simulation and measurement. The SISW provides very large bandwidth and low insertion loss. It is also a low cost solution because waveguide and planar circuit are built on the same substrate, using the same manufacturing process.

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