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Simulation and Design of a Bandpass Filter Based on Substrate Integrated E-Plane Waveguide

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***Abstract*— This paper presents a bandpass filter based on a substrate integrated E-plane waveguide (SIEW) structure for wireless applications, at X-band. The SIEW geometry allows the development of new horizontally polarized filter topologies, unlike filter structures based on substrate integrated waveguide (SIW), which present vertical polarization (perpendicular to the ground plane). The simulation of the proposed SIEW filter is carried out using Ansoft HFSS software. To evaluate the performance of the proposed structure, the frequency behaviors of the scattering parameters are obtained for a horizontally polarized excitation. In the simulation, analyses are performed for the lossless and lossy (dielectric and metallic) cases, in order to compare the obtained results. The SIEW filter is fabricated and measured using a vector network analyzer (VNA). Measurement results are in agreement with simulation ones, validating the proposed filter design and topology. The fabricated prototype resonates at 10.54 GHz, with a bandwidth of 1.20 GHz, defined for a -3 dB transmission coefficient reference level. The SIEW filter structure is easy to design and manufacture and can be used in wireless communications systems that require components with ease integration into other planar structures.**

***Index Terms*—** Substrate integrated E-plane waveguide, SIEW, laminated filter, bandpass filter.

I. INTRODUCTION

The substrate integrated waveguide (SIW) structure has been investigated in the last two decades by many researchers for microwave and millimeter wave systems applications, acting as an integration platform between planar and non-planar structures and being used in the development of passive and active components.

The SIW structure is fabricated on printed circuit board (PCB) consisting of two parallel rows of conducting cylinders inserted into the substrate and interconnected to the PCB metal plates, being invariant vertically and with electrical field polarization perpendicular to the metal plates, or ground plane [1], [2].

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Somehow, the SIW technology is equivalent to that of the traditional rectangular waveguide (which is based on H-plane type of waveguide components), with the advantage of incorporating different technologies in planar form, with low cost, low losses, ease manufacturing, light weight, reduced size, and a high-quality factor Q [3].

Recently, much effort has been dedicated to studying the SIW geometry. Several different solutions have been proposed to improve the integration with other systems and to provide reduced size components [3].

However, the SIW technology that has been used in the development of H-plane type of waveguide components in planar structure, in which the orientation of the electric field is normal to the ground plane of the circuits, cannot be used in the development of E-plane type waveguide components in planar structures, in which the electric field is parallel to the ground plane.

Meanwhile, the E-plane waveguide technology has been studied by many researchers and used in microwaves and millimeter waves applications [4]-[8], mainly because of the low losses and the possibility of selectivity of signals observed in their circuits using horizontal polarization. In particular, the use of such technology has enabled the development of many components such as stopband filters [8], bandpass filters [9], diplexers [10], [11] and multiplexers [6] on front-ends of transmitters and receivers of communications systems [12], [13]. However, because they are developed in waveguide structures, these components are heavy and large size.

Lately, the substrate integrated E-plane waveguide (SIEW) structure has been proposed [14], [15], based on the idea of developing a new technology, equivalent to that of the E-plane waveguide. The SIEW structure resembles a dielectric-filled rectangular waveguide with two horizontal perforated metal strips inserted into the structure. Thus, the polarization of the electric field is horizontal, being perpendicular to the direction of the two metal strips and parallel to the ground plane.

This work proposes the simulation and design of a new bandpass filter geometry performed using SIEW technology. Simulation is carried out using Ansoft HFSS software. A prototype is fabricated on a fiberglass substrate (FR-4) for comparison purpose.

Section II presents a description of the proposed SIEW structure and the design parameters. In Section III, the proposed compact filter performance is analyzed using Ansoft HFSS software. The simulations and measurement results are presented in Section IV. Section V summarizes the paper main conclusions.

II. THE PROPOSED SIEW STRUCTURE

The SIEW structure, illustrated in Fig. 1, is a new substrate integrated waveguide geometry formed by stacked perforated metallized dielectric layers [14], [15], separated by two equally perforated thin metal strips (printed on one of the dielectric layers side) and of two parallel rows of conducting cylinders inserted through the metallized dielectric layers and interconnected to the geometry top and bottom metal plates.

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The walls delimiting the SIEW structure are constituted by two rows of conducting cylinders parallel to y-z plane, placed on the two sides of the geometry, and interconnected to top and bottom metal plates, as shown in Fig. 1(a).

Inside of the structure the electromagnetic field is confined and propagated through the dielectric substrate. This is due to the presence of two horizontal metal strips inserted at the center of the structure, as shown in Fig. 1(b). These metal strips allow the distribution of current density throughout the longitudinal section of the structure, nearby the holes, as illustrated in Fig. 2. Wave ports are used in the computational simulation.

The physical parameters of the SIEW structure are shown in Fig. 1. The dielectric layers have the same thickness h. A distance between the conducting cylinders walls is b. The conducting cylinders walls are closely aligned with a spacing p and diameter d along the two metal plates of thickness t, at the middle of the SIEW structure. The minimal distance between adjacent conducting cylinders is defined to minimize radiation loss [16], [17].

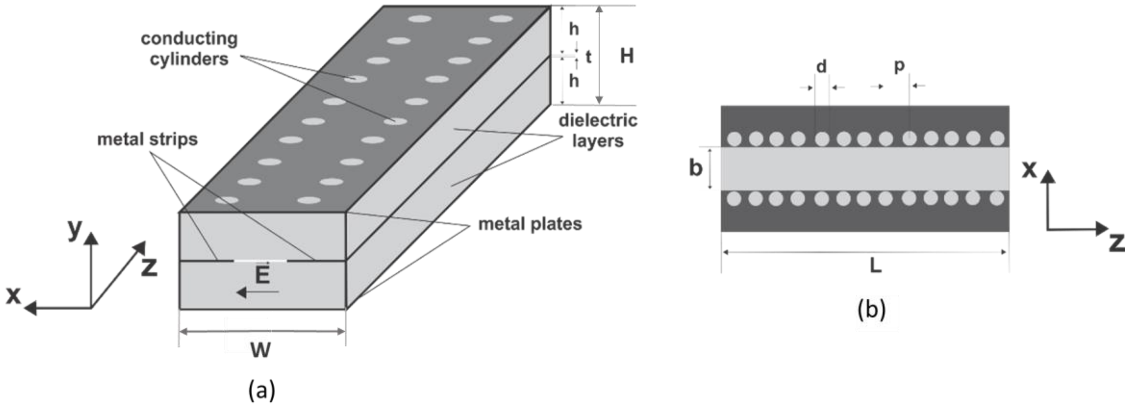

Fig. 1. SIEW filter (a) structure and (b) perforated metal strips views.

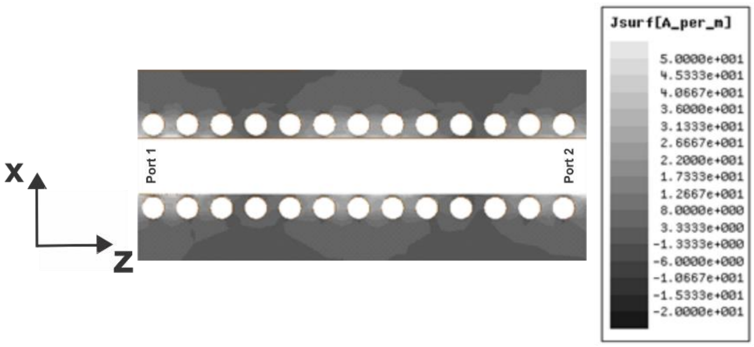

Fig. 2. Current density on the SIEW metal strips placed at the center of the structure.

The fundamental mode TE_{10} is excited at input port 1 of the structure for the determination of the scattering parameters, similarly to the excitation of conventional rectangular waveguide at X-band (8.2 GHz to 12.4 GHz). The electric field is oriented in *x* direction (Fig. 2), for horizontal polarization. The E-plane (*x*-*z* plane) is parallel to the perforated metal strips.

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The main objective of this work is to obtain one or more resonant frequencies by inserting E-plane stripline patch resonator elements between the perforated metal strips, at the middle of the filter structure, as shown in Fig. 3. Therefore, the proposed SIEW frequency response can be changed by modifying the patch resonator element original shape and dimensions, without changing any other of the filter structure parameters.

III. THE SIEW FILTER DESIGN

The SIEW filter design is shown in Fig. 3. The propagation dielectric region is delimited by two rows of conducting cylinders and two metal plates, as shown in Fig. 1. Stripline patch resonator elements are printed between the metal strips, located at the middle of the SIEW filter (Fig. 3), similarly to the metal inserts used in E-plane waveguide filter designs.

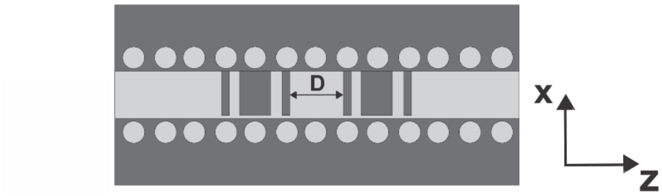

Fig. 3. Stripline patch resonator elements printed between the perforated metal strips.

In Fig. 3, the SIEW bandpass filter properties are mainly controlled by the distance D between the stripline patch resonator elements. A parametric optimization of D is carried out in order to improve the scattering parameters results. Fig. 4 shows the top view of the unit cell used in the proposed SIEW filter structure. The patch resonator unit cell is composed of three strips with different widths, but with the same length (L_1).

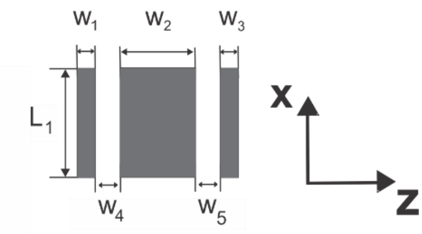

Fig. 4. Unit cell of the stripline patch resonator element (top view).

The size and coupling between the metallic patches of the resonators determine the transmission zero frequencies, characterizing a bandpass response. When the fundamental mode is applied, an equivalent to a parallel LC resonant circuit can be formed between the lengths and the widths of the resonant elements [18]-[20]. For this reason, after the preliminary scale using Ansoft HFSS software, the filter frequency response has been improved. The distance D between the resonant elements (Fig. 3) has been changed to 2.5 mm, resulting in a resonant frequency of 10.59 GHz.

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The designed SIEW structure consists of two fiberglass (FR-4) dielectric layers, with relative permittivity $\varepsilon_r = 4.4$, loss tangent $tan\delta = 0.025$, and thickness h = 4.71 mm, two rows of conducting cylinders with length L = 20 mm and separated by a distance b = 2.46 mm. The conducting cylinders are made out of copper with diameter d =1.0 mm and placed with an array spacing p = 1.5 mm. The top and bottom metal plates are made out of copper with thickness of 0.03 mm.

The simulation of the SIEW filter structure is performed using Ansoft HFSS software. The patch resonators elements have symmetry with respect to the longitudinal axis z, with reference to the center of the structure. The physical dimensions of the stripline patch resonator element (Fig. 4) are given in Table I.

TABLE I. DIMENSIONS OF THE PATCH RESONATOR ELEMENTS OF THE PROPOSED SIEW FILTER.

Resonator elements' dimensions	Value (mm)
w_1, w_3, w_4 e w_5	0.50
w_2	1.50
L_1	2.26

To investigate the effect of losses on the SIEW filter performance, simulation results have been calculated for the reflection (S_{11}) and transmission (S_{21}) coefficients for both lossless and lossy (dielectric and metallic losses) cases as shown in Fig. 5.

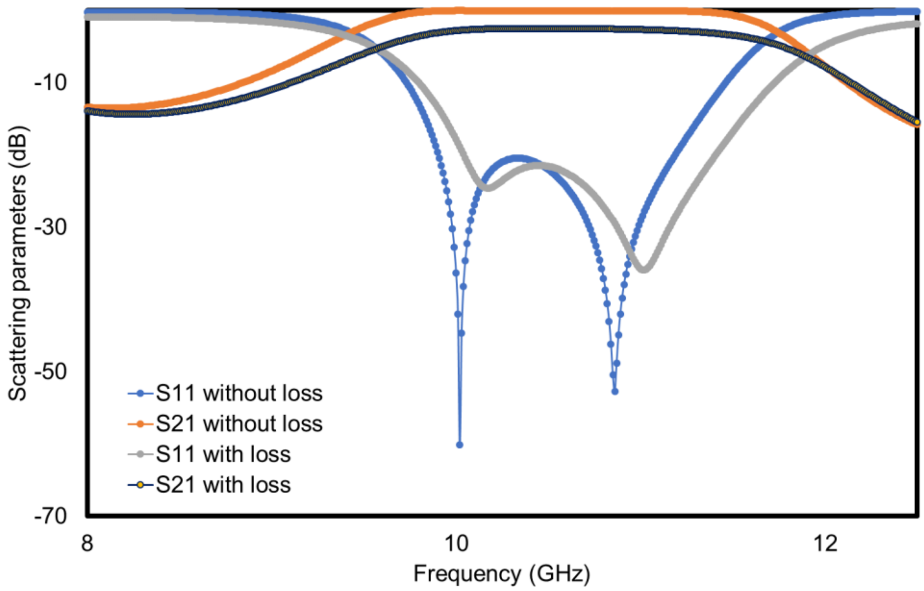

Fig. 5. SIEW filter reflection and transmission coefficients simulation results for the lossless and lossy cases.

As shown in Fig 5, the simulation results for the lossless case indicate a frequency range from 9.43 GHz to 11.75 GHz, with a bandwidth of 2.32 GHz. The center frequency, f_r, is 10.59 GHz. The simulation results for the lossy case indicate a bandwidth of 1.54 GHz, ranging from 9.89 GHz to

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11.43 GHz. At the center frequency, f_r = 10.66 GHz, the insertion loss value is 1.37 dB. The filter bandwidth results were defined for a -3 dB transmission coefficient reference level.

Table II compares the proposed SIEW filter simulation results for the lossless and lossy cases. Wave ports are used in the computational simulation. Moreover, about the same results are obtained using the simulation model with two waveguide sections like in the test setup.

TABLE II. SIMULATION RESULTS FOR THE SIEW FILTER FOR LOSSLESS AND LOSSY STRUCTURES.

Lossless structure			Lossy structure		
f_r (GHz)	S_{21} (dB)	Bandwidth (GHz)	f_r (GHz)	S_{21} (dB)	Bandwidth (GHz)
10.59	0.0	2.32	10.66	-1.37	1.54

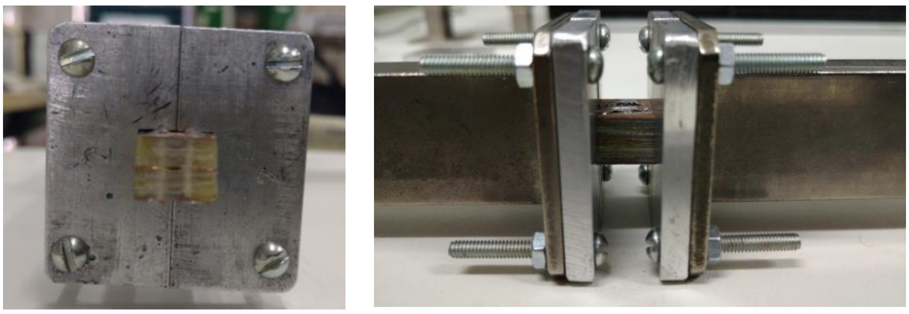
As expected, the use of lossy (dielectric and metallic) materials introduces slight reductions in the results of the transmission coefficient and bandwidth of the proposed SIEW filter, which need to be considered to guarantee accurate simulation and design.

IV. SIMULATION AND MEASUREMENT RESULTS

The proposed SIEW filter was designed for X-band applications. The overall dimensions of the manufactured planar multilayer geometry are: width W = 12.15 mm, height H = 9.51 mm, and length L = 20 mm. Photographs of the SIEW filter prototype inserted in the measurement setup are shown in Figs. 6(a) and 6(b), respectively. In the measurement setup, waveguide components available in the institutional microwave laboratory were used.

A prototype of the proposed bandpass SIEW filter was fabricated, as shown in Fig. 6, for comparison purpose. The preparation of the layers forming the structure was carried out using a LPKF ProtoMat S43 prototyping machine. The prototype assembly was carried out manually by stacking the plates, inserting the metal pins and welding.

The plane wave excitation of the structure was performed using two X-band coaxial to rectangular waveguide (WR-90) transitions which were connected to two rectangular waveguide (WR-90) sections. Two metal flanges with rectangular apertures were fabricated and used to provide mechanical support and wave transmission from the waveguide to the SIEW filter prototype and vice-versa, as shown in Fig. 6.



(a) (b)

Fig. 6. SIEW filter prototype (a) inserted in the waveguide flange and (b) measurement setup.

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To perform the filter measurement, the calibration of the vector network analyzer (VNA) was carried out using Agilent Technologies kit X11644 A. Thereafter, measurement results for the SIEW filter scattering parameters were obtained and are shown in Fig. 7. These results are summarized in Table III. All measurements were performed using a vector network analyzer (model N5230A / two-port Agilent Technologies), which operates from 300 kHz to 18 GHz.

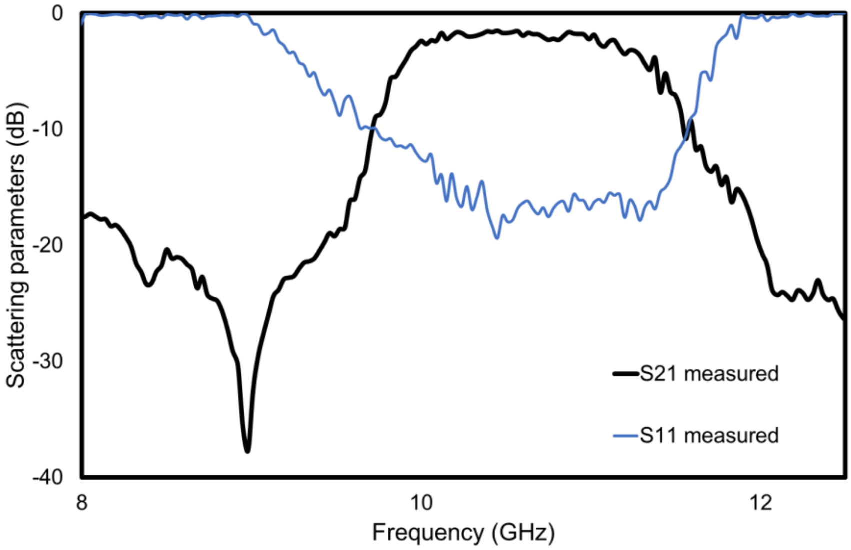

Fig. 7. Frequency response of the proposed SIEW filter prototype.

The simulation and measurement results for the transmission coefficient (S_{21}) of the SIEW filter prototype confirm the designed bandpass response, as shown in Figs. 5 and 7. The simulation results for the lossy case indicate a frequency range from 9.89 GHz to 11.43 GHz, with a bandwidth of 1.54 GHz. At the center frequency, f_r = 10.66 GHz, the insertion loss is 1.37 dB. The prototype measurement results indicate a bandwidth of 1.20 GHz, ranging from 9.94 GHz to 11.14 GHz. At the center frequency, f_r = 10.54 GHz, the insertion loss is 1.61 dB.

TABLE III. SIMULATION (WITH LOSSES) AND MEASUREMENT RESULTS OF THE PROPOSED SIEW FILTER.

Simulated results			Measured results		
f_r (GHz)	S_{21} (dB)	Bandwidth (GHz)	f_r (GHz)	S_{21} (dB)	Bandwidth (GHz)
10.66	-1.37	1.54	10.54	-1.61	1.20

As shown in Table III, excellent agreement is observed between the simulated and measured results for the resonant frequency of the proposed SIEW filter. It is also observed that the measured results for the filter bandwidth and insertion loss are in agreement with the simulated ones. The small differences are related to the presence of losses associated with the prototype manufacturing process, including welding and drilling.

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Compared to a rectangular waveguide with metal inserts in the E-plane, the manufactured prototype in printed circuit technology provided a good filtering performance with planar configuration, light weight, low profile and compact size using only two identical resonating elements.

In addition, the proposed SIEW filter structure also enables the possibility of ease of integration with other planar structures in applications using the propagation of waves with horizontal polarization, something that cannot be obtained using the traditional SIW technology.

V. Conclusion

A new bandpass filter on SIEW is proposed. Simulation and design are performed using Ansoft HFSS software. The implementation of the proposed SIEW filter has made it possible to solve in a simple way the limitation of SIW technology for the propagation of electromagnetic waves with horizontal polarization.

Measured results are in agreement with simulated results. The fabricated filter prototype exhibited a reduction of about 49.79 % in the cross-section area with respect to the WR-90 E-plane waveguide. Therefore, the proposed SIEW filter is very compact. In addition, it is ease to integrate to planar and waveguide structures, due to the multilayer structure.

The SIEW filter is a very interesting alternative to waveguide E-plane filter with metal inserts due to light weight, reduced size, low cost, and ease manufacturing. The development of new SIEW structures and applications are being considered.

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