Half-Mode Slab Air-Filled Substrate Integrated Waveguide (SAFSIW)

Nhu-Huan Nguyen*, Anthony Ghiotto†, Anne Vilcot‡, Ke Wu*, and Tan Phu Vuong‡
*University of Grenoble-Alpes – Grenoble INP, CNRS, IMEP-LaHC Laboratory, UMR 5130, Grenoble, France
†Univ. Bordeaux, Bordeaux INP, CNRS, IMS Laboratory, UMR 5218, F-33400, Talence, France
‡Poly-Grames Research Center, Polytechnique Montréal (Université de Montréal), QC, Canada, H3T 1J4

Abstract—This paper reports the proposal and development of a half-mode slab air-filled substrate integrated waveguide, a solution of compromise between half-mode air-filled substrate integrated waveguide (SIW) and half-mode SIW. Theoretical analysis and simulated results are presented to understand the operation mechanism. For experimental validation, a transition to SIW is reported and used in a back-to-back configuration. With low-cost FR-4 to cover the structure, the measured results show an insertion loss of 1.1 ± 0.17 dB together with a reflection coefficient better than -21.5 dB over the entire Ka-band. Using two transmission lines of different lengths, an attenuation of 0.298 dB/cm is obtained at 33 GHz. The half-mode slab air-filled SIW provides high degrees of freedom to control the attenuation and phase constants for the design of microwave and millimeter-wave components including couplers and leaky-wave antennas.

Keywords—Air-filled substrate integrated waveguide (AFSIW), half-mode AFSIW, slab AFSIW.

I. INTRODUCTION

The substrate integrated waveguide (SIW) reported in early 2000 [1] enables a high integration density with high performances at millimeter-wave frequencies. It provides a compromise between the air-filled rectangular waveguide and microstrip line for practical applications. Some alternative guided wave structures have been presented to further improve the latitude of design such as the air-filled SIW (AFSIW) [2] which reduces dielectric loss, and the slab AFSIW (SAFSIW) [3] which provides the control of impedance and single mode bandwidth.

To increase the integration density, some miniaturization techniques have been reported so far including slow-wave SIW [4], ridged SIW [5], folded SIW [6], half-mode dielectric-filled SIW (HM-DFSIW) [7], and half-mode AFSIW (HM-AFSIW) [8]. Among them, the half-mode structures are considered to be more practical due to the simplicity of design and integration. Furthermore, based on the open-ended nature of a half-mode structure, this topology is of high interest for coupling circuit and antenna applications.

This paper presents a half-mode SAFSIW (HM-SAFSIW) structure providing a high degree of flexibility to control the attenuation and phase constant along the transmission line. Two guided waves structures are introduced in section II with theoretical analysis, namely HM-SAFSIW and offset slab HM-SAFSIW. Then, in section III, for experimental validation, a transition from a DFSIW to an offset slab HM-SAFSIW is presented and used in a back-to-back configuration to characterize the proposed transmission line structure. Finally, this work is summarized in section IV.

II. HALF-MODE SAFSIW

A. Half-Mode SAFSIW

The SAFSIW of total width 2a consists of three layers, as shown in Fig. 1(a). In the middle layer (S2), of thickness h, a dielectric slab of width 2w1 is embedded. Sidewall slabs, of width w, are maintained to keep the integrity of the metalized via rows.

The HM-SAFSIW (Fig. 1(b)) is obtained by cutting the SAFSIW at its symmetrical plane B-B’. By doing so, the analytical equations of SAFSIW in [3] can be used to approximate the cut-off frequency of the HM-SAFSIW dominant mode.

For demonstration, a design curve shown in Fig. 2 is established for applications in Ka-band for several values of dielectric permittivity in layer S2. The cut-off frequency of the dominant mode is kept constant at fc = 20.3 GHz. The sidewall slab w is kept at 0.508 mm of width.

In this paper, the RO4003C substrate from Rogers (εr = 3.55, tanδ = 0.0027, h = 0.6 mm) is selected for layer S2 while low-cost FR-4 substrates (εr = 4.3, tanδ = 0.025, h = 0.8 mm) are used for both S1 (bottom) and S3 (top) layers for demonstration.
B. Offset Slab Half-Mode SAFSIW

To introduce more degrees of freedom, the central slab can be offset by a value of $\Delta$ as illustrated in Fig. 1(d). For $\Delta = 0$, the conventional HM-SAFSIW is obtained (Fig. 1(b)).

In this case, the analytical equations in [3] are no longer valid since the maximum electrical field of the dominant mode is concentrated in an air region instead of a dielectric region. New analytical equations should be introduced to analyze this structure.

Concerning the dominant mode, the electrical field is very weak near the metallic wall, as the effect of sidewall slab width $w_1$ can be neglected. With this assumption, the dominant mode cut-off frequency of an offset HM-SAFSIW can be approximated by

$$A_1 = \cos(k_0(a - w_1))\cot(\sqrt{\varepsilon_r}k_0w_1)$$  \hspace{0.5cm} (1)
$$A_2 = \cos(k_0(a - w_1))\sin(\varepsilon_rk_0\Delta)$$  \hspace{0.5cm} (2)
$$A_3 = \sin(k_0(a - w_1))\cos(\varepsilon_rk_0\Delta)$$  \hspace{0.5cm} (3)
$$\sqrt{\varepsilon_r}A_1 - A_2 - \varepsilon_rA_3 = 0$$  \hspace{0.5cm} (4)

where $k_0$ is the wave number in free-space and $\varepsilon_r$ is the relative permittivity of the dielectric substrate in layer S2.

To analyze the effect of $\Delta$, an embedded dielectric slab of $w_1 = 0.6$ mm and a total width $a = 2.472$ mm are chosen. The multiline method [9] is used to retrieve the attenuation constant $\alpha$ and phase constant $\beta$. The simulated attenuation constants with various values of $\Delta$ are shown in Fig. 3. The CST Microwave Studio software was used for simulation.

It can be concluded from Fig. 3 that an increase of $\Delta$ leads to a reduction of the attenuation. Since the width $a$ is fixed, an increase of $\Delta$ leads to a reduction of the cut-off frequency. In a half-mode structure, radiation loss is an important contributor to the total loss. High radiation loss occurs near the cut-off frequency. By reducing the cut-off frequency, radiation loss is reduced. Also, by increasing $\Delta$, the maximum electrical field of the dominant mode is concentrated in the air medium, which leads to a reduction in dielectric loss. Therefore, the efficiency is increased.

The simulated phase constants with various value of $\Delta$ are shown in Fig. 4. It can be observed in Fig. 4 that $\Delta$ can be modified to control the phase constant. This property is of high interest for leaky wave antenna design to generate a non-uniform distribution of $\beta$ along the structure [10]. Also, Fig. 4 shows that the leaky wave frequency range can be controlled by properly selecting $\Delta$. It should be noted that the phase constant $\beta$ could also be controlled by varying the center dielectric width $w_1$ or width $a$. This topology provides many degrees of freedom in the perspective of controlling attenuation (including radiation) and phase constants.

III. Back-to-Back Transition

In order to demonstrate the operation of HM-SAFSIW, a transition is designed to allow interconnection with instruments, and used in a back-to-back configuration as shown in Fig. 5. A center dielectric slab $w_1 = 0.6$ mm together with $\Delta = 0.7$ mm...
and \( a = 2.472 \text{ mm} \) are chosen to obtain a compromise between low attenuation and footprint. The calculated cut-off frequency is \( f_{c1} = 17.83 \text{ GHz} \) (about 1.49 times below the Ka-band).

The broadband transition from DFSIW to HM-SAFSIW is inspired by the transition from DFSIW to half-mode AFSIW reported in [8]. The dielectric is tapered to smoothly transfer electromagnetic power from DFSIW to HM-SAFSIW. The other dimensions are \( l_t = 2.2 \text{ mm} \), \( w_t = 1.4 \text{ mm} \), and \( a_0 = 3.755 \text{ mm} \).

The fabricated HM-SAFSIW is shown in Fig. 6. Two back-to-back transitions with HM-SAFSIW length of \( L = 10 \text{ mm} \) and \( L = 20 \text{ mm} \) have been fabricated to retrieve the attenuation by different lengths.

Table 1 compares different parameters of this HM-SAFSIW structure with a HM-DFSIW and a HM-AFSIW operating in Ka-band. Considering the topology shown in Fig. 1(b), the HM-AFSIW is simulated with \( w_1 = 0 \text{ mm} \), and \( a = 4.206 \text{ mm} \) while the HM-DFSIW is simulated with \( a = 2.233 \text{ mm} \) to obtained \( f_{c1} = 17.83 \text{ GHz} \) for both structures. It can be observed from Table 1 that the HM-SAFSIW presents a compromise between HM-DFSIW and HM-AFSIW in term of losses and footprint. Moreover, the HM-SAFSIW offers more degrees of freedom to control the attenuation and phase constants.

In measurement, a thru-reflect-line (TRL) calibration kit is used to de-embed the transitions from GCPW to DFSIW as shown in Fig. 6.

The simulated and measured S-parameters of the 10 mm prototype are compared in Fig. 7, where the measured and simulated results are observed to be in a good agreement. Over the Ka band, the measured reflection coefficient \( |S_{11}| \) is lower than -21.5 dB and the transmission coefficient is \( |S_{21}| = -1.1 \pm 0.17 \text{ dB} \). The measured losses are about 0.4 dB higher than the simulated losses due to the surface roughness that was not considered in simulation as well as the manual assembly. Using two transmission lines with different lengths, the obtained measured attenuation at 33 GHz is 0.298 dB/cm compared to 0.224 dB/cm in simulation.

### IV. CONCLUSION

In this paper, a flexible half-mode SAFSIW transmission line topology has been introduced with theoretical, simulated, and experimental analyses. This HM-SAFSIW provides a high degree of freedom to control attenuation and phase constants along the transmission line. A transition has been designed and used in a back-to-back configuration for experimental validation. This new topology is believed by the author to be of high interest for coupling and leaky-wave structures.

### V. ACKNOWLEDGMENT

The authors would like to thank Mr. Traian Antonescu, Poly-Grames Research Center, Montréal, QC, Canada and Mr. Nicolas Corrao, IMEP-LaHC Research Center, Grenoble, France, for their valuable support, and the region Rhône-Alpes for supporting the SCUSI project.

### REFERENCES


