Received December 9, 2018, accepted December 25, 2018, date of publication January 21, 2019, date of current version February 8, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2893483

Compact Leaky SIW Feeder Offering TEM Parallel Plate Waveguide Launching

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This work was supported in part by the European FP7 Project DORADA, in part by the European Horizon 2020 Project CSA-EU and in part by EPSRC project EPSRC EP/P025129/1.

ABSTRACT A planar and low-cost parallel-plate waveguide (PPW) launcher based on substrate integrated waveguide (SIW) technology is proposed. It can launch the fundamental TEM mode with a collimated wave front into a PPW structure while also being low profile and easy to fabricate. The launcher is implemented using a network of SIW transmission lines and its design is based on the leaky-wave (LW) theory. In our proposed structure, a selection of the SIW lines is made to leak power into the desired PPW region by means of a partially reflective surface, enabling planar wave front propagation of the TEM mode where efficiency values of over 90% are achieved. Measurements of a fabricated prototype are also reported at 15 GHz to demonstrate the design procedure and validate structure operation. When compared with similar co-axial and metallic waveguide launchers, our proposed SIW structure represents a compact, integrated, and unique design solution which may be useful to feed planar parallel-plate slot arrays and end-fire antennas. In addition, our novel and simple approach for PPW excitation can also be applied to other parallel-plate-based guides, low-cost transitions, and compact dividing/combining circuits for a new antenna and non-radiating LW feed systems at microwave and millimeter-wave frequencies.

INDEX TERMS Feeding network, leaky-waves (LWs), parallel-plate waveguide (PPW), substrate integrated waveguide (SIW), TEM mode.

I. INTRODUCTION

Many slot array antennas are implemented in waveguide technology for applications such as radar and satellite communications. When considering the design of these antennas, the excitation and feed system of the array becomes of key importance to ensure efficient aperture illumination and element feeding. One key benefit of this is that waveguides can couple power very efficiently to other configurations using transitions [1]. In fact, feeding losses can be very small in comparison to other feedlines, such as microstrip, when considering corporate feed networks at microwave and millimeter-wave frequencies [2]. Therefore, not only can the antenna array be implemented using waveguide technology, but also integrated with the feed system. This allows for the entire antenna, the radiating elements, and the feeding transmission line, to be contained within the same structure and made uni-planar or multi-layer [2], [3].

On the other hand, waveguide and more conventional array structures can be bulky and expensive to manufacture and the use of alternative technologies has been proposed in the literature for many years. For instance, substrate integrated waveguide (SIW) technology allows for confined wave propagation between two conducting plates by means of two parallel rows of vias connected to the top and bottom conductors [4]. This is similar to a metallic waveguide, but in PCB form. SIW is a versatile technology for microwave frequencies, being also compatible with microstrip and other planar technologies. When considering similar parallel-plate waveguide (PPW) structures for radiating applications, a very simple planar antenna can be designed by etching a particular slot layout (or patterned aperture) on the upper conductor. Motivations can be to integrate a planar feeding system for efficient antenna and planar waveguide operation. Nevertheless, the uniform and planar wave front required for efficient array illumination can be challenging and increase the feed system complexity when considering compact and fully integrated design requirements.

Different feed system arrangements have been investigated previously using various approaches with application to slot antenna arrays etched on the top conducting layer of PPWs. For example, the concept of integrated launching of a uniform TEM mode for slot arrays was introduced in [2], where a coaxial-fed rectangular metallic waveguide was placed under the parallel-plate substrate. This feed system operated at 11.5 GHz with an efficiency of almost 50% by means of coupling slots on top of the waveguide. Moreover, this technique required a multi-layer implementation which increased the volume and complexity of the launching system.

In order to avoid such multilayer structures, several approaches to uniformly distribute the TEM field have been proposed for more planar implementations. For example, the use of metallic walls was proposed in [5] as a series of T-junctions inside an air-filled PPW. Dense post-walls were also employed in [6] acting as narrowband coupling windows, which required careful design for each cavity to properly set the phase and amplitude along the structure. While the amplitude stays fairly constant with variations of ± 5 dB and ± 3 dB in [5] and [6], respectively, uniform phase can be difficult to achieve for the exited field at the design frequency. For example, a decrease of 60° in phase was observed in [5] for the T-junctions cavities while phase variations between 10° and −20° were observed for the post-wall structure in [6]. These structures reduce the launcher size while sacrificing design and manufacturing simplicity, but yet do not obtain a very uniform amplitude and phase distribution.

Alternatively, the application of quasi-optical concepts to create a planar and fully integrated structure was studied in [7] where reflected waves eventually formed a uniform field distribution starting from a cylindrical-wave. However, this clever feeding network can be considered electrically large when comparing the size of the planar wave front eventually generated. This is due to the use of two parabolic reflectors required to generate the desired wave front, where the main reflector was at least $5\lambda_o$ in size. Moreover, a partially reflective surface (PRS) based on leaky-wave (LW) theory with probe pin excitation was also necessary to illuminate these reflectors. Generally speaking, these feed system arrangements can be more time consuming to design than the antenna itself and some systems have also been fed by two coaxially fed probe pins (perpendicular to the ground plane) to shape and control the field launched inside the PPW using a PRS for leakage in the form of a cylindrical-wave, such as in [7] and [8]. This type of feed arrangement can easily feed the reflector system, however, at the same time, does not allow for simple integration and compact feeding of linear slot arrays. Also, some undesired mutual coupling effects between the sources can be problematic in these designs requiring some compensation techniques to enable the desired PPW field launching and antenna radiation when considering grid-based slot arrays.

In this paper we present a compact, simple and low-cost configuration for TEM launching into a PPW (see Fig. 1) by suitably and originally combining SIW technology and LW theory whilst operating close to the open stopband frequency for the structure. This enables simple and compact collimated wave-front formation into the PPW. Unlike [7] and [8], where a cylindrical-wave was generated, our proposed feed arrangement can immediately achieve a uniform plane-wave front with a direction of propagation perpendicular to one sidewall of the SIW. This launcher is simply fed by a single-input 50-Ω microstrip line and defines a single-layer implementation for slot arrays and other planar PPW feed systems. The proposed feeding network reduces fabrication complexity and consists of conventional microwave elements such as a T-junction in SIW technology, where having one sparse via wall which acts as a PRS[7]–[10] for power leakage, avoiding the use of other mechanisms, such as reflectors, to obtain a planar TEM wavefront in PPW.

Due to this application of LW theory, and by suitable design, planar TEM propagation is obtained very near the PRS via side wall. This avoids the physical space typically required between the input transmission line or feed point and the generated wave front as in previous designs [5]–[8]. In our case, the uniform phase front is formed at the leaky SIW side wall, and, when considering operation at microwave and millimeter-wave frequencies, this can lead to minimal conductor and dielectric losses, mainly, due to the compact and efficient nature of the launcher and the generated field profile.

The proposed planar PPW launcher has also applications as an end-fire antenna or as the feeding network to other parallel-plate based guides, new low-cost transitions, and compact dividing/combining circuits. Being very useful for applications such as radar or communications systems. To the authors′ knowledge, such a compact, simply-fed, and low-cost design, using well-known SIW microwave elements to efficiently launch the TEM mode into PPW with a planar wave front, has not been reported previously, fully designed, fabricated and measured.

In order to achieve a launching efficiency of over 90% for our TEM PPW launcher, the size of the leaky PRS aperture is set to be $2.5\lambda_o$, making the design more compact and efficient when compared to the other previously reported configurations [5]–[8]. Also, in order to achieve leakage normal to this PRS side wall, the complex propagation constant and field profile of the leaky SIW should be accurately characterized [11], [12]. This can provide TEM propagation in the broadside direction with respect to the SIW launcher aperture and with a uniform amplitude and phase field profile (as illustrated in Fig. 1). As it will be further described in the paper, the respective variations in the magnitude and the phase of the launched TEM mode are 1.5 dB and 5° or less along the aperture in the PPW region, which is a significant improvement when compared to other designs found in the literature.

It should be mentioned that some initial findings were investigated in [13] but no theoretical analysis or general design guidelines were provided. Moreover, we have employed a thinner substrate for this structure from [13] while working at the same frequency, in order to reduce microstrip radiation losses at the input considering microwave and millimeter-wave frequencies. In this paper, we also aim to report a complete design procedure of the planar PPW launcher (see Fig. 1), which includes for the first time supporting numerical analyses, full-wave simulations, and experimental verifications. It will also be discussed in the next few sections that when we compare our newly designed and optimized structure to [13], the aperture distribution in the parallel-plate region is more uniformly generated (in magnitude and phase) defining an improved feed system design. In addition, measurements are reported at 15 GHz for a fabricated two-launcher test circuit prototype and numerical findings and full-wave simulations corroborate the measurements and design.

In Section II a step-by-step design procedure for the SIW launcher is outlined as well as full-wave simulations and the relevant field distributions inside the feed system. In addition, the LW theory, design principles, and dispersion analysis that model the behavior of the SIW structure are accurately described. As a proof of concept, a newly designed two-port, non-radiating test structure has been manufactured, whose measurements and characteristics are presented in Section III. Some conclusions are provided in Section IV.

II. DESIGN OVERVIEW

The PPW TEM launcher has two main components: the well-known microstrip-to-SIW transition and the open T-junction. Each passive section must be properly designed for optimum feed system operation. The microstrip-to-SIW transition is set to be a tappered SIW section, see Fig. 1, due to its better performance than the typical tappered microstrip line for this structure [14].

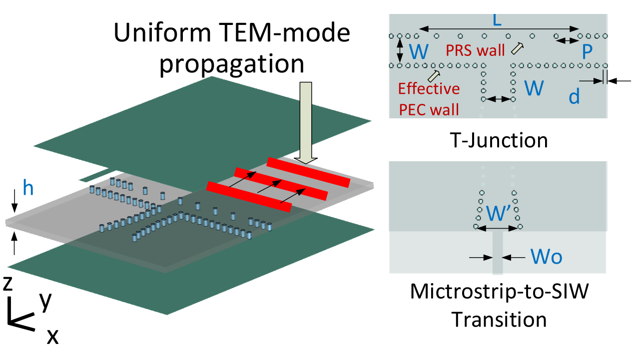

FIGURE 1. Schematic for the proposed PPW-TEM mode launcher consisting of the microstrip-to-SIW transition, an SIW T-junction with one sparse row of vias defining a partially reflective screen (PRS), and the PPW region.

In addition, it should be highlighted that the modified SIW section with the sparse via sidewall defining the PRS supports a perturbed TE_{10} mode which couples to the TEM mode of the PPW in the form of a non-radiating LW for propagation into the PPW region. Thus, careful modal analysis of the dispersion for this quasi-TE_{10} leaky mode, and its complex wavenumber, is essential for accurate design and for optimum operation of the proposed PPW launcher in SIW technology.

A. SIW T-JUNCTION AND LW THEORY

This is the primary component of the launcher, which consists of a modified H-plane T-junction power divider for equal power distribution within the PPW region. This structure is similar to a two-sided periodic structure for LW radiation into free-space, but designed here for a non-radiating application; i.e. an SIW to PPW transition and with 50-Ω microstrip feeding. The more conventional design of this T-section structure has been widely explained in the literature, for instance in [9] and [15]–[17]. As mentioned, our design is further based on LW theory applied to SIW structures [1], [18] and considering optimized broadside LW radiation from periodic structures [19].

As it is well known, LW modes have a complex propagation wavenumber [12], [19] ($k_x = \beta - j\alpha$) due to radiation losses or leakage. This can be used to effectively characterize the propagation inside the leaky SIW sections, where leakage can occur into the PPW region. These losses can be negligible if the ratio between the via post separation P and their diameter d is small enough ($P/d < 2$) [4], hence a wall of dense vias can act as perfect electric conductor (PEC). Otherwise, the power will be leaked and the losses will become significant, behaving as a PRS [20]. For our proposed launcher, these losses are necessary to couple power into the TEM mode of the PPW. Thus one of the walls of the T-junction should ensure the vias are separated as to not satisfy the $P/d < 2$ ratio condition. This ensures controlled leakage into the PPW region as illustrated in Fig. 1.

To design this leaky PRS in SIW technology, several general guidelines are established from previous SIW-based leaky wave antennas [12] while the bounded SIW section was designed following the equations provided in [4]. In particular, to design the PRS, it is necessary to analyze the complex propagation constant of the relevant LW mode. The leakage rate α (i.e., the imaginary part of the complex propagation constant) sets the fraction of power that couples into the PPW TEM mode and it depends on the separation P and the diameter d of the vias. The higher this separation the higher the leakage rate is observed on the opposite side of the SIW-to-PPW transition. At the same time, the phase constant β (i.e., the real part of the complex propagation constant) establishes the direction of propagation of the TEM mode in the PPW [19].

The uniformity of the amplitude and the phase can be obtained by selection of the LW propagation constant.

In particular, broadside leakage from the SIW T-junction into the PPW region can be achieved by satisfying the so-called beam-splitting condition which is based on having approximately equal phase and leakage constants; i.e., it is necessary to work slightly above the cutoff frequency (where $\beta \approx \alpha$ and with $\beta > \alpha$). Also, it is known that the leakage angle θ_m increases if β increases according to $\theta_m = \sin^{-1}(\sqrt{(\beta/k_0)^2 - (\alpha/k_0)^2})$ [19], thus, with an increase in frequency above cutoff, the larger is the angle θ_m. The simulated behaviors of the electric fields for the structure for these different relations between β and α are depicted in Fig. 2.

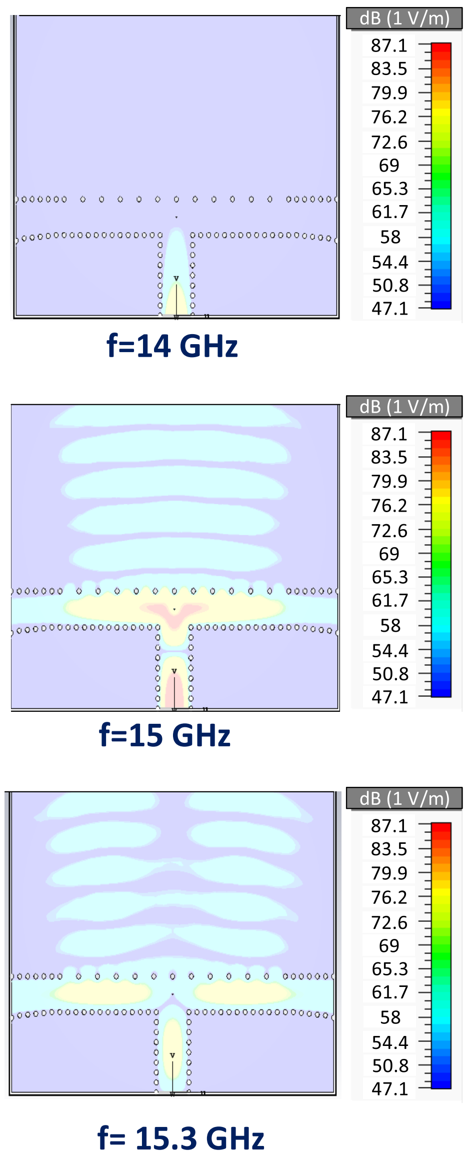

FIGURE 2. **The simulated electric field generated by the launcher. On top, the frequency of operation is below the cutoff frequency ($\beta < \alpha$); i.e., the TEM mode is not propagating. In the center, the structure is working at the design frequency where $\beta \approx \alpha$. It can be observed that the TEM mode is propagating with a uniform phase front and perpendicular (or broadside) to the leaky SIW sidewall. On the bottom, $\beta > \alpha$, therefore the propagation angle for the bound TEM wave is not normal to the launcher.**

Once the width W of the bounded SIW section is known, a dispersive analysis of the SIW for different values of P and d must be completed [12]. This analysis can be performed using an adapted version of the transverse equivalent network (TEN) as previously defined in [11] and [12] and the approaches presented in [21]. In our case, see Fig. 3, the TEN is not terminated with the radiation impedance as the PPW is not truncated anymore. Instead the characteristic impedance of an infinite PPW is now defined for the developed circuit model (Fig. 3) for analysis and design.

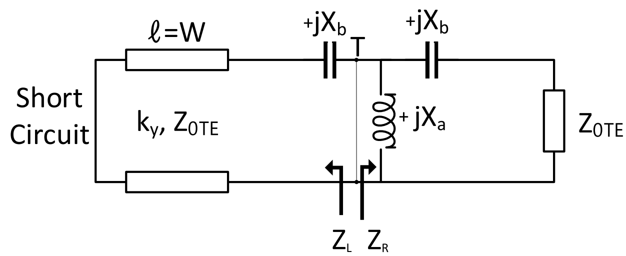

FIGURE 3. **A modified TEN circuit model for the proposed SIW structure enabling bound TEM-mode launching inside a PPW, which is different when compared to [11] since antenna radiation into free-space was considered in that work. In our representation, starting from the left, the non-leaky SIW sidewall is represented by a short circuit, the transmission line equivalents to the SIW width, the leaky PRS wall is modeled using Marcuvitz's approach [21] for inductive posts in PPWs, and the characteristic impedance for the infinite PPW region.**

The transverse resonance equation (TRE) at the T section in Fig. 3 is enforced to determine the dispersion behavior of the leaking section. This equation is $Z_L(k_y) + Z_R(k_y) = 0$ where

$$Z_L(k_y) = j\tan(W \cdot k_y) \cdot Z_{OTE}(k_y) + j \cdot X_b \tag{1}$$

$$Z_R(k_y) = \frac{jX_a \cdot (Z_{OTE}(k_y) + jX_b)}{jX_a + Z_{OTE}(k_y) + jX_b} \tag{2}$$

and $k_y = \sqrt{k_0^2\varepsilon_r - k_x^2}$ is the transverse wavenumber inside the SIW, X_b and X_a are the capacitances and inductance whose equations are explained in [21], and $Z_{0_{TE}}$ is the characteristic impedance for the TE_{10} mode.

Dispersion analysis considering no dielectric and conductor losses is reported in Fig. 4. It can be observed that the frequency where $\beta = \alpha$ is very close to 15 GHz. It should be also noticed that this leaky-mode dispersion analysis is needed to tune the pair of values W and P which determine the proper leaky SIW dimensions that provide the desired beam-splitting condition; i.e. $\alpha \approx \beta$ at the design frequency of 15 GHz.

Next, we can easily find the appropriate value for the PRS wall aperture length L related to α setting the launching efficiency as 90% so $L = 2.3/\alpha$ [13]. The side arms of the T-junction can be left open to ease the design and prototyping process as negligible power is maintained at the end of the arms due to the high launching efficiency. This launching efficiency can be obtained at the edge of the launcher as depicted in Fig. 5, where the efficiency is plotted for two different cases (lossless and lossy conditions). It can be observed that 90%

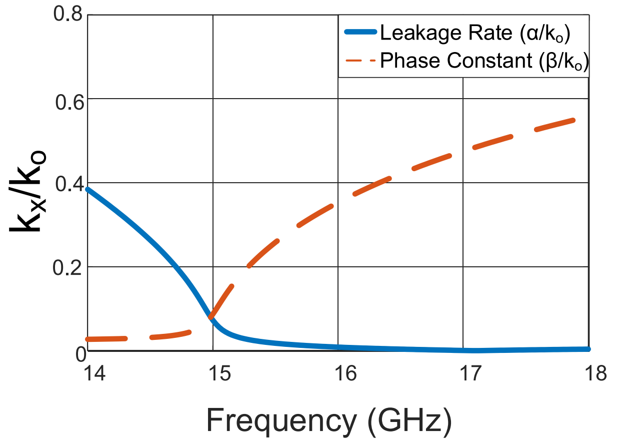

FIGURE 4. Results of the dispersive analysis for the SIW launcher designed to work at about 15 GHz for $W = 6.8$ mm, $P = 4.5$ mm and $d = 1$ mm with $\varepsilon_r = 2.2$ and thickness $h = 0.79$ mm. The solid lines represent the complex solution of the TRE defined by Eqs (1) and (2); normalized LW phase constant β/k_0 in red dashed line and α/k_0 in blue.

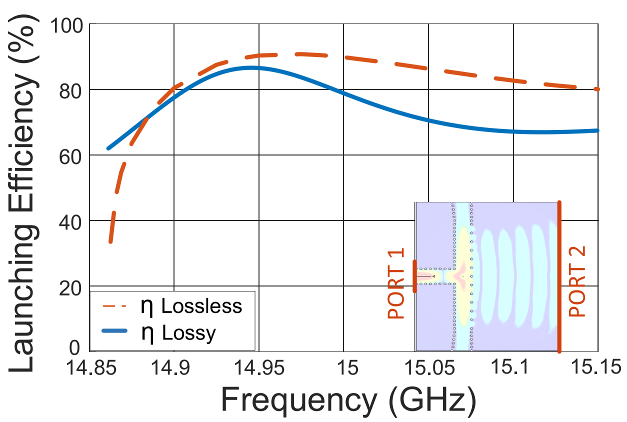

FIGURE 5. Launching efficiency (η) obtained at the edge of a single launcher structure (shown in inset on the right). This launching efficiency was calculated directly from the linear values of the simulated transmission coefficients. The dashed red line shows the launching efficiency obtained for lossless conditions, while the blue line includes dielectric and conductor losses. It can be observed that the peak launching efficiency is frequency shifted to about 14.95 GHz when considering a lossy substrate.

of efficiency is reached for the lossless case while the values for the lossy scenario (substrate dielectric losses as well as structure conductor losses) are over 85% but slightly shifted in frequency (less than a 0.5% frequency shift). The observed differences in the lossless and lossy case simulations can be attributed to substrate and conductor losses, in that some small changes to the loads which model the leaky PRS sidewall as well as the wave impedances are evident. Regardless, a good agreement is observed with the theoretical LW model (Figs. 3 and 4) and the efficiency simulations of the structure (Fig. 5) in terms of the design frequency.

It should also be mentioned that when using a short circuit to model the PEC wall as in Fig. 3, a perfect 180° reflection is defined in the analysis for the complex wave. However, the row of vias actually have an inductive behavior that introduces a phase shift of about 150° [18] which is slightly different from the perfect short circuit. Following [18] it is possible to achieve a more accurate result and the PEC wall can be modeled with complex circuit elements.

The calculation steps for the parameters of interest W, d, P, L, β and α can be summarized as the following:

- Find the width W of the bounded SIW section for a frequency of interest using equations in [4].
- Dispersive analysis of the SIW for different values of P and d satisfying the splitting condition ($\beta = \alpha$) at the operating frequency by using the TEN presented in Fig. 3.
- Use the calculated α in the previous step to find the length of the PRS L using $L = 2.3/\alpha$ for an efficiency of 90%.

B. EXCITED FIELDS AND MODES

As mentioned in the previous sections, different field profiles and modes can be excited within the SIW feed structure. In order to confirm that the modes excited in the structure are the expected ones, E-fields have been simulated in the corresponding sections, inside the bounded SIW section and the TEM mode along the width of the PPW region. The simulated field components for these modes, the TE_{10} inside the SIW section and the TEM mode inside the PPW, are depicted in Fig. 6. These modes are compared to the ones existing in a typical SIW and PPW. For the TE_{10} mode, it is shown that there is no electric-field component along the direction of propagation ($E_y = 0$) whereas the magnetic component is

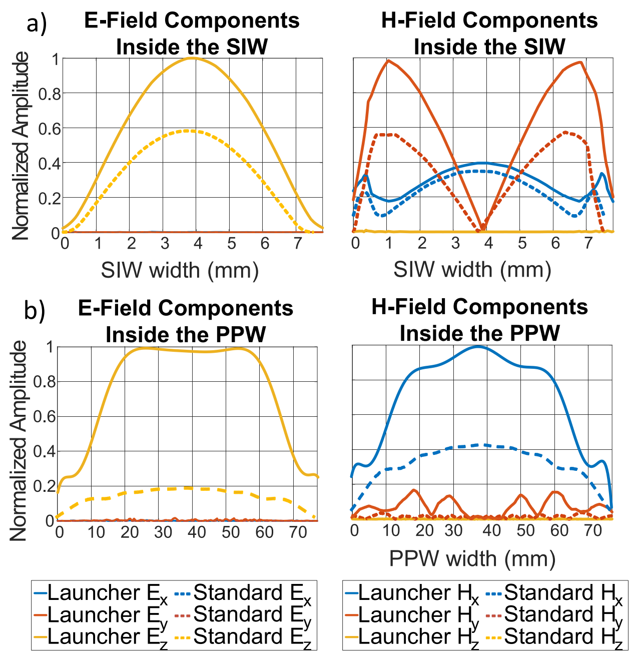

FIGURE 6. The normalized field components within the end-to-end configuration compared to the fields existing in a standard SIW or PPW along the x-direction: (a) electric and magnetic field components for the excited TE_{10} mode inside the bounded SIW section, (b) the TEM mode inside the parallel-plate at a distance of 10 mm from the aperture.