Periodic Leaky-Wave Antenna for Millimeter Wave Applications Based on Substrate Integrated Waveguide

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***Abstract*—Substrate integrated waveguides (SIW) are built up of periodically arranged metallic via-holes or via-slots. The leakage loss of SIW structures increases with the distance between the via-holes or via-slots. An open periodic waveguide with a large via distance supports the propagation of leaky-wave modes and can thus be used for the design of a leaky-wave antenna. In this paper, this leakage loss is studied in detail and used to design a periodic leaky-wave antenna. The proposed concept represents an excellent choice for applications in the millimeter-wave band. Due to its versatility, the finite difference frequency domain method for periodic guided-wave or leaky-wave structures is used to analyze the characteristics of the proposed periodic leaky-wave antenna. Two modes (TE_{10} and TE_{20}) are investigated and their different leaky-wave properties are analyzed. Based on the proposed leaky-mode analysis method, a novel periodic leaky-wave antenna at 28–34 GHz is designed and fabricated.**

***Index Terms*—Finite difference frequency domain, periodic leaky-wave antenna, substrate integrated waveguide.**

I. Introduction

SUBSTRATE integrated waveguide (SIW) technology has been studied very extensively in recent years and has by now become a widely applied technique in planar microwave circuit design [1]–[4]. These waveguide-like structures are fabricated in planar form and are built up by periodically arranged metallic via-holes or via-slots [4] and take advantage of the well-known characteristics of conventional rectangular waveguides, namely, its high Q-factor and high power capacity, as well as its low losses. Though they have been studied for the use in antenna applications [5], [6], SIW structures have only been considered in the form of standard rectangular waveguides or cavities for slot antennas. In this paper, a novel concept is proposed that takes advantage of the increasing leakage loss for large via distances, which favors the forming of leaky-wave modes in the structure. As a result, a periodic leaky-wave antenna can be designed based on SIW technology.

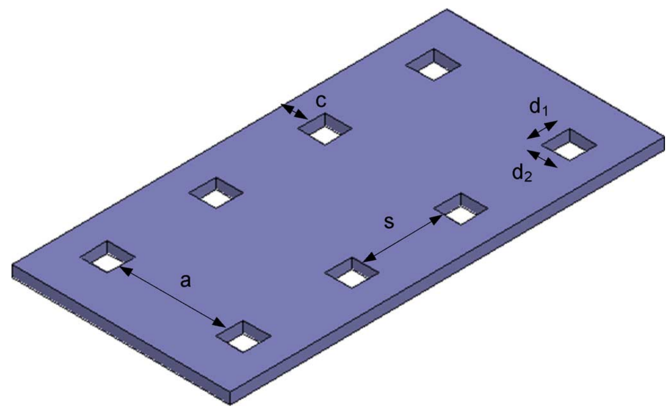

Fig. 1. Periodic leaky-wave antenna of SIW version.

The operation principle of leaky-wave antennas has been well known for many years [7], [8]. There are two different kinds of leaky-wave antennas; one type is related to uniform guided-wave structures [9]–[11], while the second consists of an array of periodic guided-wave structures [12]–[15]. The first kind of leaky-wave antennas provides radiation into the forward quadrant and can yield scanning from broadside to forward end fire directions. The scanning range for periodic leaky-wave antennas reaches from backward end fire through broadside directions into a part of the forward quadrant. The dominant mode on the former type represents a fast wave, while the latter type is a slow wave structure. As a result, the dominant mode on periodic leaky-wave antennas does not radiate and radiation is achieved by using one of its space harmonics. A general SIW-based leaky-wave antenna architecture is shown in Fig. 1. Obviously, it belongs to the group of periodic leaky-wave antennas.

The analysis and design of leaky-wave antennas mainly consists of the extraction of two parameters, namely the phase constant β and the leakage constant α. A number of numerical methods such as the transverse resonance method and the spectral-domain method have been used to extract the complex propagation constant. In this paper, the finite difference frequency domain (FDFD) method is selected due to its high versatility for analyzing the characteristics of the SIW leaky-wave antenna [16]–[18]. In recent years, this method has been successfully applied to extract the propagation characteristics of various types of SIW structures and is therefore directly applicable to the analysis of SIW leaky-wave antennas. For the analysis of this spe-

Manuscript received November 20, 2008; revised April 07, 2009. First published June 30, 2009; current version published February 03, 2010. This work was supported in part by the Natural Sciences and Engineering Research Council (NSERC) of Canada.

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Digital Object Identifier 10.1109/TAP.2009.2026593

cific type of structure, the domain decomposition technique has to be used because the simulation of SIW leaky-wave antenna is carried out both in the substrate region and the air region. The two modes TE_{10} and TE_{20} in the SIW will be investigated in order to get their leakage mode characteristics and to obtain the appropriate space harmonics.

II. FDFD Algorithm

When the FDFD method is used to resolve the characteristics of guided-wave structures, a nonsymmetrical standard eigenvalue problem is obtained if the equivalent resonant cavity model is used [17]. As an alternative, it is possible to use a standard FDFD method [16] by eliminating the longitudinal field components. In order to obtain more accurate results, in our case, a nonsymmetrical generalized eigenvalue problem is obtained [18],

$$\mathbf{A}\mathbf{x} = \gamma \mathrm{B}\mathbf{x} \tag{1}$$

where γ is the propagation constant, which may be a complex number depending on the type of problem. The vector $\mathbf{x}$ is equal to $\mathbf{x} = [\mathbf{h}_{\mathrm{x}}, \mathbf{h}_{\mathrm{y}}, \mathbf{e}_{\mathrm{x}}, \mathbf{e}_{\mathrm{y}}]^{\mathrm{T}}$ for a wave propagation along the z-direction.

We introduce a shift-and-invert (SI) Arnoldi technique [19]–[21] in order to obtain a direct solution of the generalized eigenvalue problem in (1). The SI Arnoldi method can be used to compute a small number of eigenvalues close to a given shift and/or the associated eigenvectors of a large matrix pair. In the application of periodic guided-wave structures, we are interested in computing only some eigenvalues in the complex plane, which represent the complex propagation constants. In (1), for eigenvalues close to a shift σ, we obtain

$$\mathbf{A}\mathbf{x} = \gamma \mathbf{B}\mathbf{x} \Leftrightarrow (\mathbf{A} - \sigma\mathbf{B})\, x = (\gamma - \sigma)\, \mathbf{B}x. \tag{2}$$

Thus

$$(\mathbf{A} - \sigma\mathbf{B})^{-1}\mathbf{B}\mathbf{x} = \theta\mathbf{x} \tag{3}$$

where

$$\theta = \frac{1}{\gamma - \sigma}.$$

As shown in Fig. 2, the entire simulation domain includes the substrate sub-domain and the air sub-domain in the case of leaky-wave antennas. As a result, the concept of domain decomposition is introduced in the simulation.

III. Parametric Analysis

It is well known that the wave propagation for the dominant mode in periodic leaky-wave antennas is slow ($\beta > k_0$) relative to free-space velocity, and the dominant mode itself does not radiate. The radiation of periodic leaky-wave antennas is originating from space harmonics introduced by periodicity,

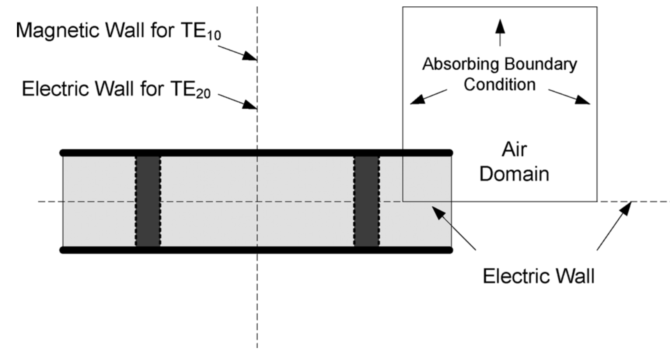

Fig. 2. Transversal view of the SIW simulation domain.

$$\beta_n d = \beta_0 d + 2n\pi \tag{4}$$

where d is the period, and β_0, the fundamental space harmonic, represents the propagation constant β of the dominant mode for a periodic guided-wave structure. When β_n takes different values, the related space harmonic can be forward or backward in nature. The necessary condition for the radiation of a space harmonic is

$$\frac{\beta_n}{k_0} < 1. \tag{5}$$

In a practical antenna design, usually only a single main radiated beam is needed and thus β_{-1} is selected. As a result, when the frequency increases, the β_{-1} space harmonic starts to radiate from a backward end fire direction. With a further increase in frequency, the beam moves from the backward end fire direction into the back quadrant. For even higher frequencies, the beam moves toward broadside radiation, then traverses broadside direction, and moves into the forward quadrant. However, the range in the forward quadrant is usually limited by the emergence of the β_{-2} beam at the backward end fire direction or by a higher guided-wave mode [8].

The beam direction of periodic leaky-wave antennas can be calculated from

$$\sin\theta_m \approx \frac{\beta_{-1}}{k_0} \tag{6}$$

where θ_m is the maximum beam angle measured in broadside direction and

$$\beta_{-1} = \beta_0 - \frac{2\pi}{d}. \tag{7}$$

The next section includes a detailed discussion of the radiation characteristics for the two leakage modes TE_{10} and TE_{20} in SIW structures.

A. *Leaky-Wave Mode Related to the* TE_{10} *Mode*

For the analysis of this specific case, a magnetic wall is introduced in the center of the SIW as shown in Fig. 2. The propagation constant of the dominant mode can be approximated as

$$\beta_0 = \frac{2\pi}{\lambda}\sqrt{1-\left(\frac{\lambda}{2a'}\right)^2} \tag{8}$$

where a' is the equivalent width of the waveguide and is larger than the inner width a (as shown in Fig. 1) of an SIW [4], [22]. From (5) and (8) we obtain the condition, for which the dominant mode does not radiate as

$$\frac{\beta_0}{k_0} = \sqrt{\varepsilon_r}\sqrt{1-\left(\frac{\lambda}{2a'}\right)^2} > 1. \tag{9}$$

Obviously, if the condition is fulfilled at a certain low frequency, the dominate mode does not radiate at higher frequencies. The permittivity of the substrate is selected according to the low frequency of leaky-wave antennas to $\varepsilon_r > 2$.

The phase constant for the TE_{10} leaky-wave mode is obtained from (7) and (8) as

$$\beta_{-1} = \frac{2\pi}{\lambda}\sqrt{1-\left(\frac{\lambda}{2a'}\right)^2} - \frac{2\pi}{d}. \tag{10}$$

From (10), we can conclude that the period d is a key factor in the design of leaky-wave antennas as it directly defines the antenna's frequency range with a smaller period d resulting in a higher operating frequency. Although the design of periodic leaky-wave antennas also depends on the leakage constant, we can use (9) and (10) to determine its frequency range and select an approximate value for the substrate permittivity.

In a next step, the FDFD method will be used to extract the leakage constant and the phase constant of SIW leaky-wave antennas accurately. As shown in Fig. 1, the dimensions are selected to an SIW width $a = 10$ mm, rectangular metal slot dimensions $d_1 = 0.8$ mm and $d_2 = 0.8$ mm, and a distance between the slots $s = 4.8$ mm. This yields a period length $d = s + d_1 = 5.6$ mm. An RT/duroid 5880 substrate with a thickness t of 0.787 mm, a permittivity $\varepsilon_r = 2.2$, and a loss tangent $\tan\delta = 0.009$ is selected in the simulation.

The value of the phase constant is very important in determining the main beam direction, as well as for identifying single or multi beam operation. For the presented analysis we assume an infinitely extended substrate (c is infinite) in order to highly simplify the simulation model. The phase constants obtained from these approximate equations are very similar to the results obtained for the case of a finite substrate. However, the main beam direction needs to be multiplied with a factor $(\varepsilon_0/\varepsilon)^{0.5}$ according to the Snell's law. Please note that if c is infinite, the dominant mode is a fast wave. In this analysis, we only focus on the calculation of the first space harmonics.

Figs. 3 and 4 show the angle of maximum radiation calculated from (6) and the normalized leakage constant. In Fig. 3, a comparison of the results of the FDFD method and the approximate relation in (10) ($a' = 11$ mm) illustrates that the latter is a suitable approximation for evaluating the phase constant of SIW leaky-wave antennas. From Fig. 4, we observe a stop band that emerges for beam angles close to zero.

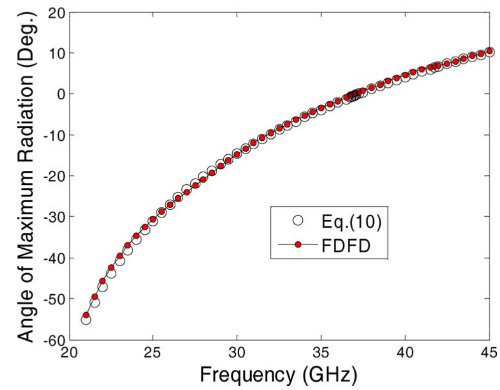

Fig. 3. Comparison of the angles of maximum radiation for the SIW leaky-wave antenna for the TE_{10} mode, $s = 4.8$ mm and $d_1 = 0.8$ mm.

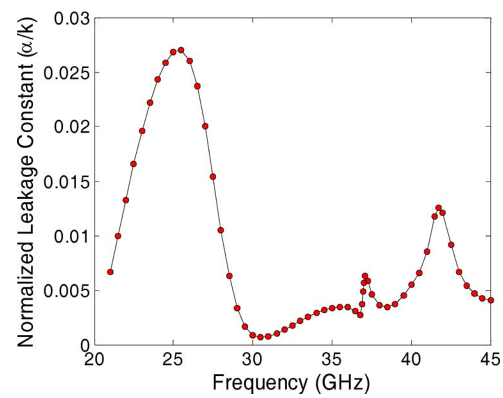

Fig. 4. Normalized leakage constant for the SIW leaky-wave antenna for the TE_{10} mode, $s = 4.8$ mm and $d_1 = 0.8$ mm.

For modified dimensions $s = 4.0$ mm and $d_1 = 1.6$ mm (note that the overall periodical distance $d = s + d_1 = 5.6$ mm keeps unchanged), the angle of maximum radiation and the normalized leakage constant calculated with the FDFD method are shown in Figs. 5 and 6, respectively. As the period d keeps unchanged, the phase constants are expected to remain almost constant, which is proved by comparison of the results in Figs. 3 and 5. On the contrary, the leakage constants in Figs. 4 and 6 are different. However, the influence of the stop band is very small in both cases.

B. *Leaky-Mode Related to the* $\mathrm{TE}_2 0$ *Mode*

For the analysis of the TE_{20} mode, an electric wall is introduced in the center of the SIW as shown in Fig. 2. The propagation constant of the dominant mode can be calculated approximately as

$$\beta_0 = \frac{2\pi}{\lambda}\sqrt{1-\left(\frac{\lambda}{a'}\right)^2}. \tag{11}$$

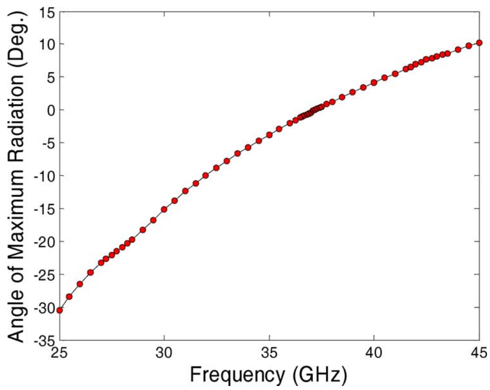

Fig. 5. Angles of maximum radiation of the SIW leaky-wave antenna for TE_{10} mode, $s = 4.0$ mm and $d_1 = 1.6$ mm.

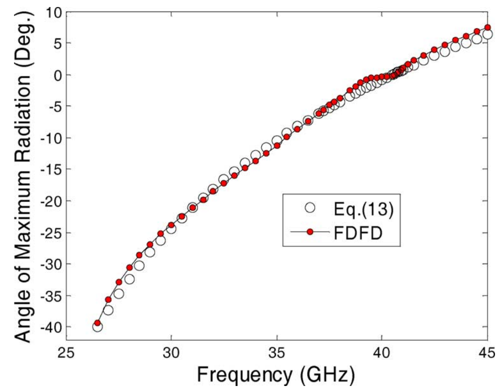

Fig. 7. Comparison of the angles of maximum radiation of the SIW leaky-wave antenna for the TE_{20} mode, $s = 4.8$ mm and $d_1 = 0.8$ mm.

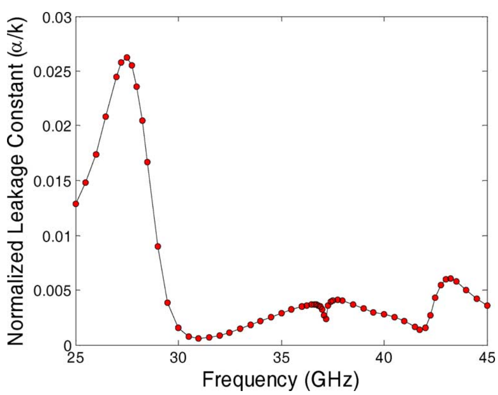

Fig. 6. Normalized leakage constant of the SIW leaky-wave antenna for TE_{10} mode, $s = 4.0$ mm and $d_1 = 1.6$ mm.

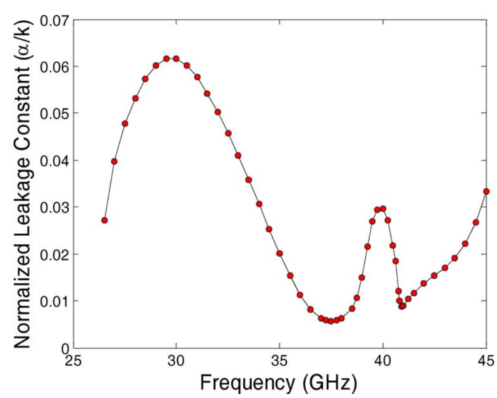

Fig. 8. Normalized leakage constant of the SIW leaky-wave antenna for the TE_{20} mode, $s = 4.8$ mm and $d_1 = 0.8$ mm.

From (5) and (11), we obtain the condition, for which the dominant mode does not radiate as

$$\frac{\beta_0}{k_0} = \sqrt{\varepsilon_r}\sqrt{1-\left(\frac{\lambda}{a'}\right)^2} > 1. \tag{12}$$

By comparing (9) and (12), we observe that the lowest frequency of the TE_{20} mode, for which the dominant mode does not radiate, is higher than that of the TE_{10} mode. Therefore, it is better to use a substrate with higher permittivity.

The phase constant of the leaky-wave mode can be calculated from (7) and (11) as

$$\beta_{-1} = \frac{2\pi}{\lambda}\sqrt{1-\left(\frac{\lambda}{a'}\right)^2} - \frac{2\pi}{d}. \tag{13}$$

According to (13), the frequency for obtaining a certain beam angle in TE_{20} mode is higher than in TE_{10} mode .

The FDFD method can also be used in the case of TE_{20} mode for extracting the leakage constant and phase constant of SIW leaky-wave antennas. The dimensions are selected to an SIW width $a = 10$ mm, rectangular metal slot dimensions $d_1 = 0.8$ mm and $d_2 = 0.8$ mm, and a slot distance $s = 4.8$ mm, which yields a period $d = s + d_1 = 5.6$ mm. Again we assume an infinitely extended substrate ($c = \infty$) for the simulation. An RT/duroid 5880 substrate with a thickness t of 0.787 mm is selected.

Figs. 7 and 8 show the angle of maximum radiation and the normalized leakage constant, respectively. In Fig. 7, a comparison of the FDFD method and (13) ($a' = 11$ mm) illustrate once more that the approximation in (12) is suitable to evaluate the phase constant of SIW leaky-wave antennas. Furthermore, from Fig. 8, we also observe that the influence of the stop band is small.

For different dimensions $s = 4.0$ mm and $d_1 = 1.6$ mm ($d = s + d_1 = 5.6$ mm keeps unchanged), the angle of maximum radiation and the normalized leakage constant obtained from the FDFD method are shown in Figs. 9 and 10, respectively. Again, for an unchanged period d, the phase constants remain almost constant, which is proved by comparison between the results in Figs. 7 and 9. The leakage constants shown in Figs. 8 and 10 are again different. A comparison of Figs. 4 and 8, as well as Figs. 6 and 10, leads to the conclusion, that the radiation characteristics of the TE_{20} mode are better than for the TE_{10} mode.

C. Finite Substrate

In practical applications c is finite, as shown in Fig. 1. This section describes an analysis of the impact of different values for c on the characteristics of SIW leaky-wave antennas.

Based on the analysis results in the previous section, a leaky-wave antenna operating in TE_{20} mode will be investigated. The dimensions are the same as for the case in Fig. 7, i.e., an SIW

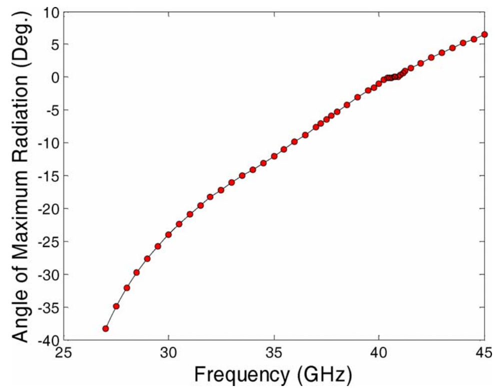

Fig. 9. Angles of maximum radiation of the SIW leaky-wave antenna for the TE_{20} mode, $s = 4.0$ mm and $d_1 = 1.6$ mm.

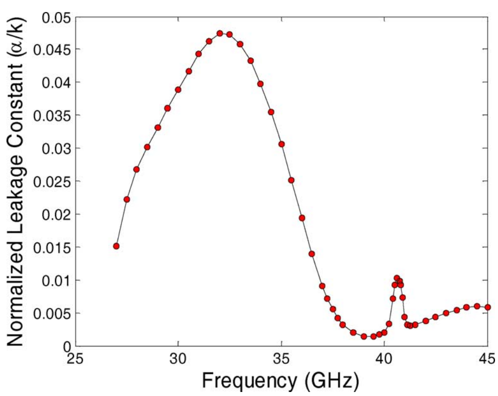

Fig. 10. Normalized leakage constant of the SIW leaky-wave antenna for the TE_{20} mode, $s = 4.0$ mm and $d_1 = 1.6$ mm.

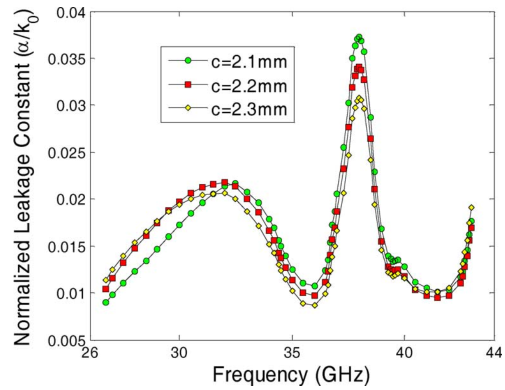

Fig. 11. Normalized leakage constant of the SIW leaky-wave antenna for the TE_{20} mode, $s = 4.8$ mm, $d_1 = 0.8$ mm.

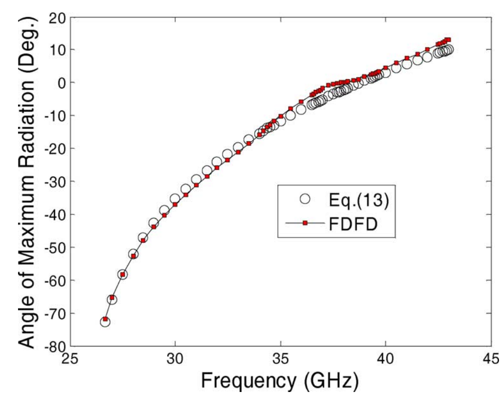

Fig. 12. Angles of maximum radiation of the SIW leaky-wave antenna in free space radiation for the TE_{10} mode, $s = 4.8$ mm, $d_1 = 0.8$ mm and $c = 2.2$ mm.

width $a = 10$ mm, rectangular metal slot dimensions $d_1 = 0.8$ mm and $d_2 = 0.8$ mm, a slot distance $s = 4.8$ mm, a permittivity $\varepsilon_r = 2.2$, a loss tangent $\tan\delta = 0.009$, and a substrate thickness $t = 0.787$ mm. Three different values for c are investigated, i.e., $c = 2.1$ mm, 2.2 mm, and 2.3 mm. As shown in Fig. 2, the entire FDFD simulation domain includes the substrate sub-domain and the air sub-domain and the concept of domain decomposition is introduced into the simulation. Fig. 11 shows the normalized leakage constants for the three selected c values obtained from the FDFD method. From Fig. 11, we observe that the antenna has the best leakage behavior for $c = 2.2$ mm.

The angle of maximum radiation for $c = 2.2$ mm is shown in Fig. 12. Again, (13) is used for an approximate evaluation of the angle. Note, that for this case the wave number for free space radiation in (6) needs to be used. In addition, according to Snell's law, the angle of maximum radiation needs to be multiplied with a factor $(\varepsilon_0/\varepsilon)^{0.5}$ at the interface between the substrate and free space. From Fig. 12, it is observed that multiple reflections and refractions occurring at the interface have only a small influence on the phase constant. However, their impact on the leakage constant is relative large.

IV. Measurement

Based on the analysis in Section III, a TE_{20} mode leaky-wave antenna is designed and fabricated. Although the leakage characteristics in Fig. 11 are not as good as for the result presented in Fig. 8, an SIW leaky-wave antenna operating in the range of 28–34 GHz is designed in order to verify the conception and the design rules for SIW leaky-wave antenna proposed here. The dimensions are selected according to the values given in Fig. 11, and c is selected to 2.2 mm.

A. Feed

The excitation of the TE_{20} mode is realized by combining two TE_{10} modes with opposite phases. As shown in Fig. 13, a microstrip line equally divides the input signal in two parts and excites the TE_{10} mode in two narrow SIW branches. The travelling wave is a quasi-TEM mode on the microstrip line and a TE_{10} mode in the SIW. In order to realize the opposite phase combination of the two TE_{10} modes, different lengths of microstrip and SIW are selected according to

$$\frac{2\pi}{\lambda_0}\sqrt{\varepsilon_e}\cdot\Delta l - \frac{2\pi}{\lambda}\sqrt{1-\left(\frac{\lambda}{2a_0}\right)^2}\cdot\Delta l \approx \pi \qquad (14)$$

where $\Delta l = l_1 - l_0$ as indicated in Fig. 13, and ε_e is the effective permittivity of the microstrip. Finally, the two SIW branches are combined into a wide SIW branch representing the leaky-wave antenna in order to excite its required TE_{20} mode.

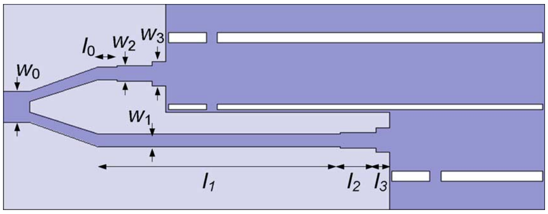

Fig. 13. Topology of TE_{20} mode feed.

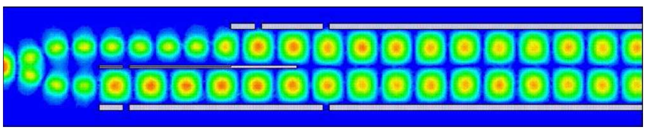

Fig. 14. Field distribution of feed extracted from Ansoft HFSS.

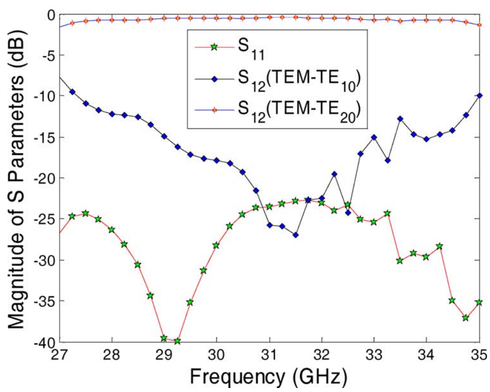

Fig. 15. S parameters of feed calculated with HFSS.

The dimensions of the feed are selected to $w_0 = 2.4$ mm, $w_1 = 1$ mm, $w_2 = 1.2$ mm, $w_3 = 1.9$ mm, $l_0 = 1.4$ mm, $l_1 = 17.9$ mm, $l_2 = 2.6$ mm, and $l_3 = 1$ mm. The width a_0 of the two narrow SIW branches is 4.8 mm.

The simulation of the proposed structure is carried out with the help of Ansoft HFSS, offering a significant reduction in simulation time. Fig. 14 shows the calculated field distribution and confirms the development of the desired TE_{20} mode in the wide SIW branch at a central frequency of 31 GHz. In addition, a detailed S-parameter simulation for the feed design in Figs. 13 and 14 is performed. Two ports, one for a quasi-TEM mode at the input of the microstrip line, and one for TE_{10} and TE_{20} modes at the end of the wide SIW branch are introduced. Fig. 15 shows the S-parameter results obtained from HFSS, which prove a good performance in terms of input matching of the feed as well as suppression of the TE_{10} mode.

B. Measurement of the SIW Leaky-Wave Antenna

The dimensions of the presented leaky-wave antenna have been outlined in Section IV. A Rogers RT/Duroid 5880 wit $\varepsilon_r = 2.2$ and $\tan\delta = 0.009$ is used for fabrication. According to the simulated leakage constant calculated from the FDFD method, the antenna length is selected to $L/\lambda_0 \approx 7$. The manufactured prototype of the SIW periodic leaky-wave antenna is shown in Fig. 16 and the simulated and measured results for the return loss are shown in Fig. 17. The return loss is lower than -15 dB over the entire frequency range of 28–34 GHz.

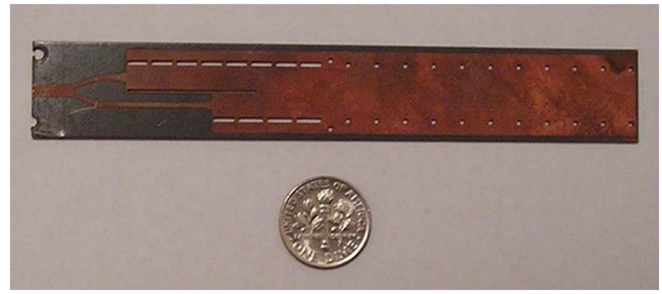

Fig. 16. Photograph of the manufactured the SIW TE_{20} leaky-wave antenna.

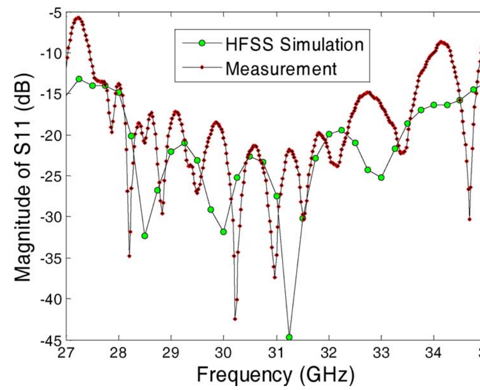

Fig. 17. Measured and simulated return loss of the leaky-wave antenna.

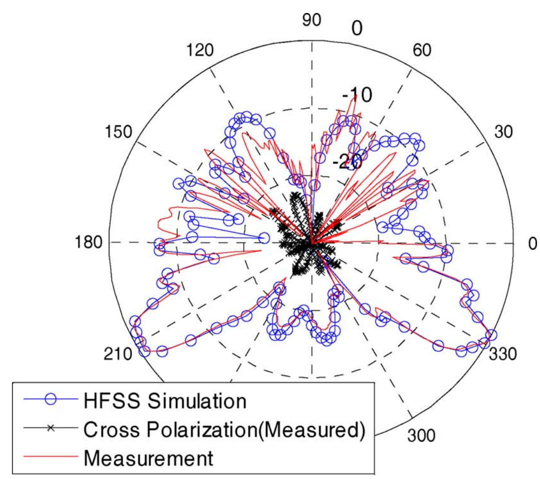

Fig. 18. Measured and simulated H plane pattern at 31 GHz.

The simulated and measured far-field patterns at the center frequency of 31 GHz in the H-plane (the plane of the substrate) are shown in Fig. 18. As expected from the results obtained in Fig. 12, the antenna radiates at an angle of about $-30°$. Furthermore, the measured maximum cross polarization in the plane is reasonably low (less than -20 dB). The gain in simulation and measurement are 9.514 dB and 9.3 dB at 31 GHz, respectively. The E-plane (the plane vertical to the propagation direction) pattern is shown in Fig. 19. A good agreement for the radiation patterns in Figs. 18 and 19 verifies the design procedure and analysis of the presented SIW leaky-wave antenna.

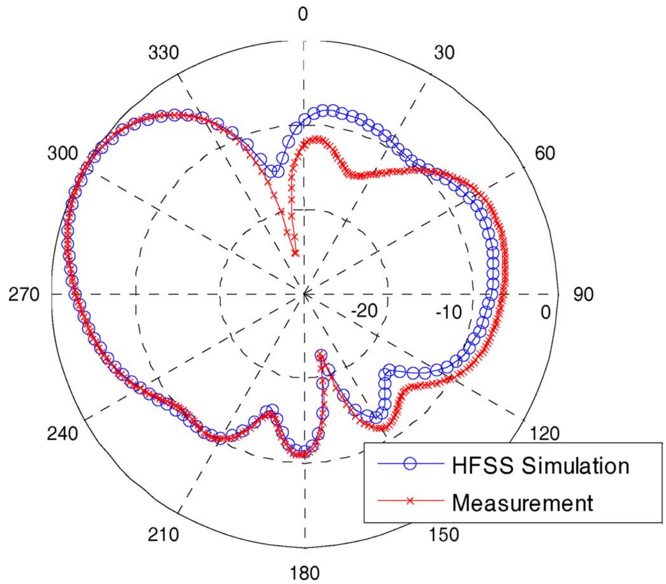

Fig. 19. Measured and simulated E plane pattern at 31 GHz.

V. Conclusion

The simulation and measurement results have validated the proposed design and analysis method of an SIW-based periodic leaky-wave antenna. The design of such an antenna is based on the leakage loss of SIW structures, which increases with distance between the via-holes or via-slots. An open periodic waveguide with a large via distance supports the propagation of leaky-wave modes and can therefore be used for the design of a leaky-wave antenna. The developed SIW-based structure is very suitable for applications in the millimeter-wave band. Important design characteristics have been identified, such as the better radiation properties of the TE_{20} mode over the TE_{10} mode. Moreover, the substrate permittivity and the periodical distance are key parameters for the performances such as the directivity, operating frequency and efficiency. Future work includes a more detailed investigation for solving the problem related to the observed stop band.

Acknowledgment

The authors would like to thank Miss S. Winkler of the Poly-Grames Research Center, Département de Génie Électrique, École Polytechnique de Montréal, for her great assistance in the revision of the manuscript.

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