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Volume 6- Number 3- Summer 2014 (1-6)

# Design Investigation of a Modified HMSIW Leaky Wave Antenna

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Received: January 1, 2013-Accepted: August 3, 2014

*Abstract*— **In this paper, a new leaky wave antenna (LWA) is introduced. The proposed antenna radiates through a dielectric aperture created by half mode substrate integrated waveguide (HMSIW) technique. A sample antenna is designed and simulated and its radiation characteristics are investigated. It is illustrated that half conical radiation pattern is provided by the proposed antenna. The designed antenna is also fabricated and its radiation properties are measured. Results show that the proposed antenna has the advantages of wide bandwidth, enhanced scanning angle and high gain in addition to low profile, low fabrication cost, low weight. Radiation patterns of antenna at different frequencies are theoretically calculated and compared with simulated ones. Good agreement between simulated and calculated results proves the validity of the theory presented for the calculation of radiation patterns. Moreover, its common features including high directivity and beam steering capability which make it suitable for millimeter-wave applications.**

***Keywords- leaky wave antenna; beam steering; half mode substrate integrated waveguide (HMSIW)***

## I. INTRODUCTION

Leaky Wave Antennas (LWAs) in planar technology offer a simple solution to obtain a low-cost and easy-fed directive radiation patterns from a low-profile single layer circuit. The first LWA using microstrip technology was introduced in [1], and later it was studied in detail [2]. Recently, a half-width microstrip (HWM) LWA was proposed in [3]. This kind of LWA provides an easier feeding method than the full-width microstrip LWA, since it can directly operates by its fundamental $EH_1$ mode. In [4] a LWA is designed based on microstrip structure. But, due to conductor loss, its radiation efficiency is low.

Recently Substrate Integrated Waveguide (SIW) technology is widely used as a low cost implementation of different planar microwave components and antenna structures [5], since it provides advantages such as high *Q*-factor, low conductor loss and easy integration with planar circuits. In [6] the leakage of electromagnetic fields is obtained by increasing the distance between each two vias of the SIW and the LWA radiates through the side wall of the structure. In [7] the LWA radiates through a long slot etched on the broad wall of the SIW. In [8-9] LWAs are designed and investigated based on the composite left/right handed SIW concept. In these designs the leaky wave is radiated through inter-digital slots etched on the broad wall of SIW. The proposed antennas in [8-9] have the ability of beam steering from backfire to end-fire including the broadside direction. In [10] the leakage power is radiated through a series of inclined slots on the broad wall of SIW. The proposed antenna in [10] is able to produce different polarizations depending on which port of the antenna is excited. In [11] the leaky wave is radiated through a periodic set of transverse slots on the broad wall of the SIW. In [12] half mode substrate integrated waveguide (HMSIW) technique is used to design a LWA. In this structure, a long SIW is cut at its symmetrical plane and the leaky wave is radiated through the open side of the HMSIW. A conical radiation pattern is provided by the proposed antenna.

In this paper HMSIW technique is used to design and investigate a LWA which radiates through a dielectric aperture of the structure. The proposed antenna is the modified form of the presented antenna in [12]. Results show that for the proposed antenna, radiation characteristics including impedance bandwidth, scanning angle and antenna gain are significantly improved while its 3D radiation pattern is halved. Furthermore, the theory of operation of the LWA is discused and analytical calculation of radiation patterns is presented. Radiation patterns of antenna at different frequencies are calculated and compared with those obtained by simulation and measurement. It is shown that good agreement between different results is observed.

## II. THEORY OF OPERATION

When the dominant mode propagates in a SIW, the maximum value of E-field exists at the vertical center plane along the transmission direction. In addition, because of the large width to height ratio (*WHR*) of the SIW structure, the normal magnetic field is zero at this plane. As a result, the symmetrical plane of the structure can be considered as a magnetic wall. Based on this theory, the SIW structure can be bisected into two halves along the magnetic wall. Each half is called Half Mode SIW (HMSIW) and nearly supports half of the original field distribution. Furthermore, since the *WHR* is large, the leakage from the magnetic wall is negligible and the total power almost remains within the structure. So, a HMSIW provides electromagnetic characteristics of the original SIW, while its size is reduced by nearly 50%. The reduction of size in HMSIW may lead to lower conductor and dielectric loss in compare with the SIW. The dominant mode field distributions of the SIW and HMSIW are illustrated in Fig. 1.

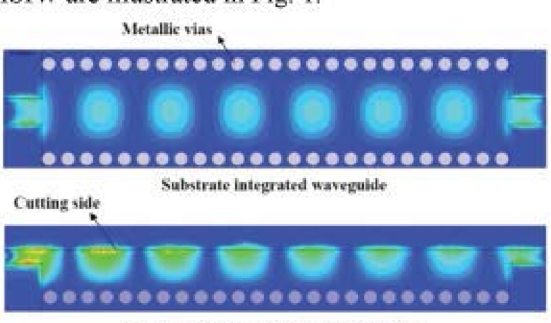



Fig. 1 Field distribution of dominant mode in SIW and HMSIW structures

## III. ANTENNA CONFIGURATION AND DESIGN

Fig. 2 shows the proposed antenna configuration and its geometrical parameters. The parameters $d$, $p$, $W_1$, $d_1$ and $W_{50}$ are via diameter, via period, HMSIW width, dielectric aperture width and 50 Ω microstrip line width respectively. In order to match the input feed line to the HMSIW structure, the width of feed line is halved which is denoted by $W_{50}/2$. A tapered mirostrip line with length of $L_T$ and end width of $W_T$ is used to improve impedance matching condition. The values of $L_T$ and $W_T$ are adjusted for the best return loss. The antenna is terminated by a 50 Ω matching load.

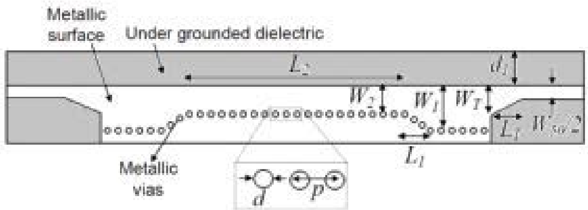



Fig. 2 Configuration of the proposed LWA antenna

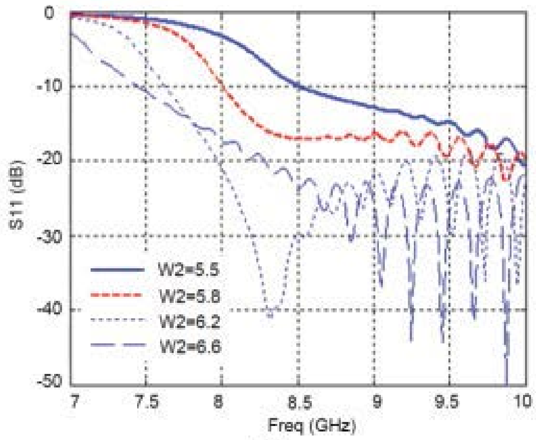
The key parameter which determines the frequency range at which the effective leakage and the return loss are favorable, is the width of half mode wave guide at the leakage part of antenna denoted by $W_2$ [12]. In fact, if $W_2$ is selected equal to $W_1$, the leakage is decreased so that it can be neglected as discussed in part II. In order to obtain good power leakage and better return loss in the desired frequency range, $W_2$ should be less than $W_1$ and its value should be tuned by numerical investigation.

To study the effect of $W_2$ on reflection coefficient and insertion loss, a parametric study is carried out using HFSS software. Results for $S_{11}$ and $S_{12}$ are illustrated in Fig. 3. It can be seen that the frequency band in which the effective leakage is taken place, is greatly affected by $W_2$. To improve $S_{11}$, a section of HMSIW with tapered width from $W_1$ to $W_2$ is adopted. The length of tapered part $L_1$ is adjusted numerically by software in order to get the desired return loss.

Also the effect of antenna aperture length, $L_2$, on beamwidth and insertion loss of the proposed LWA was studied numerically. It can show that higher radiation efficiency and narrower beamwidth could be obtained by increasing the antenna length $L_2$ [12]. This fact is clearly illustrated in Fig 4(a) and Fig. 4(b). In Fig. 4(a), simulated H-plane radiation pattern is shown for different values of antenna length. It can be observed that the beamwidth decreases as $L_2$ increase. The percentage of radiated leakage power based on the definition in equation (1)

$$\text{Leakage Power} = 1 - |S_{11}|^2 - |S_{12}|^2 \qquad (1)$$

using the simulated values of $S_{11}$ and $S_{12}$, is shown in Fig. 4(b) versus $L_2$ , aperture length. It can be seen that radiated power is increased by increasing $L_2$, which reveals that antenna efficiency is increased.

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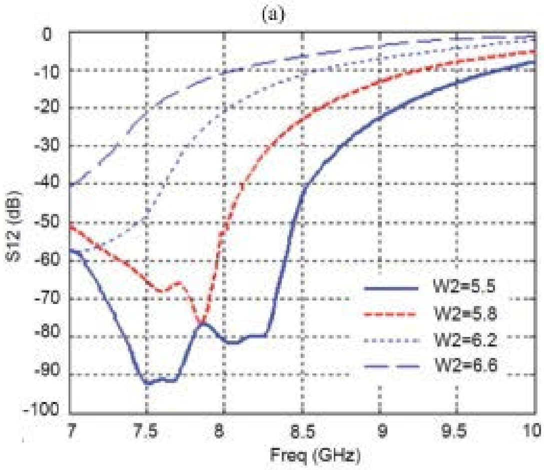
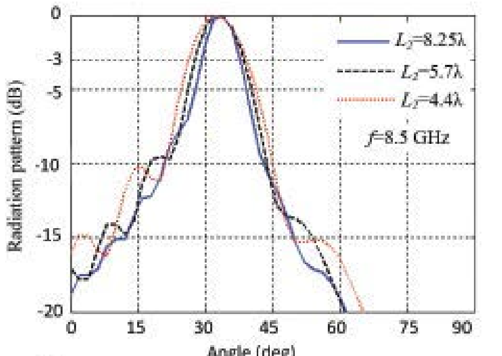
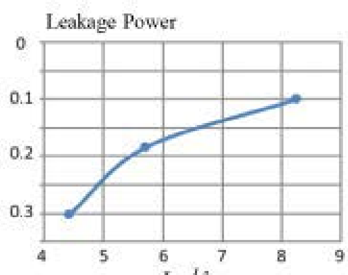



(b)

Fig. 3 The effect of $W_2$ on a) reflection coefficient, b) insertion loss of the proposed antenna versus frequency




(a)




(b)

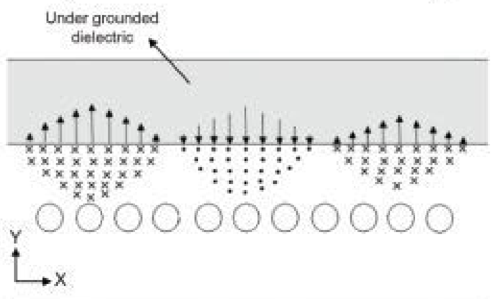
Fig. 4 The effect of $L_2$ on beamwidth and radiation efficiency, a) simulated H-plane radiation pattern at 8.5 GHz for different values of $L_2$, b) simulated leakage power versus normalized $L_2$

Based on the above discussion, a sample of the proposed LWA with the dimensions listed in Table. I is designed, simulated and its radiation properties are investigated. One model of the designed antenna is also fabricated and its radiation characteristics are measured. The photo of the fabricated antenna is shown in Fig 5. The rear side of antenna is completely metallic. Rogers Duroid 5880 with the relative permittivity of 2.2 and thickness $h$ = 0.5 mm is used as the substrate.

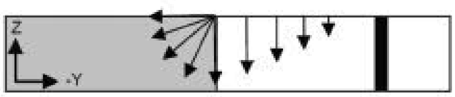
TABLE I. GEOMETRICAL PARAMETERS OF THE PROPOSED ANTENNA

| Parameter | Value (mm) | Parameter | Value (mm) |
|---|---|---|---|
| $p$ | 1.6 | $W_1$ | 7.92 |
| $d$ | 1 | $W_T$ | 6 |
| $d_1$ | 15 | $L_T$ | 13.38 |
| $L_2$ | 291.45 | $W_{50}/2$ | 1.54 |
| $W_2$ | 5.8 | | |

Electric field pattern in HMSIW structure for the proposed antenna is shown in Fig. 6. Also, the mechanism of the waves radiated thorough the dielectric aperture of the LWA is shown in Fig. 6.




(a)




(b)

Fig. 6 Electric field pattern in HMSIW across the dielectric aperture, a) top view, b) side view.

## IV. RESULTS AND DISCUSSION

Measured and simulated $S$ parameters of the proposed antenna are shown in Fig. 7. It can be seen that for measured results, over the frequency range of 8 GHz to 10.47 GHz, both $S_{11}$ and $S_{12}$ are less than -10 dB, and so LWA radiates efficiently. Also the obtained results by measurement agree well with those obtained by simulation.

In Fig. 8 measured and simulated radiation patterns at 8.5 GHz and 9 GHz are illustrated. The patterns are plotted at principal E-, ($x$-$y$) and H-planes, ($x$-$z$), which shows a very good agreement between simulated and measured results. Moreover, measured

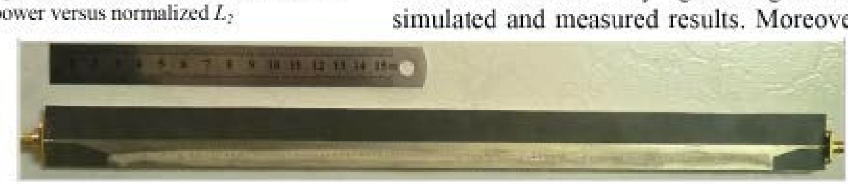


Fig. 5 Photo of the fabricated antenna

radiation patterns at 8.25 GHz, 9 GHz, 9.6 GHz and 10 GHz are shown in Fig. 9. Results show that the antenna beam is steering in an angular region by frequency variation. Radiation patterns at E- and H-plane reveal that the proposed antenna has a half conical 3-dimentional pattern which effectively can radiate in two quarters of free space based on port excitation. For the proposed antenna in [12], the LWA provides a full conical 3-dimentional pattern which effectively can radiate in all four quarters of space based on port excitation.

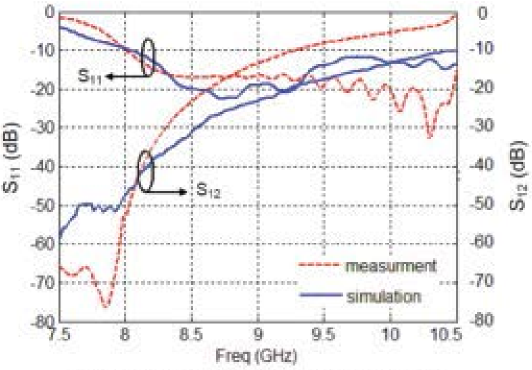



Fig. 7 $S$ parameters of the proposed antenna

It can also be observed that by increasing frequency, narrower beam and consequently higher gain is provided, which is caused by enlargement of dielectric aperture length $L_2$ due to the frequency change. Front to back ratio (*FTBR*) in H-plane is also improved by frequency enhancement. The detailed results are summarized in Table II.

The effect of dielectric aperture width $d_1$ on antenna radiation performance including bandwidth at which the effective leakage is occurred, gain and *FTBR* are also listed in Table II. The case $d_1$=0 refers to the LWA structure proposed in [12]. Results in Table II show that for the proposed antenna in this paper, impedance bandwidth, gain and the steering angular sector are enhanced. Also, radiation pattern of the presented antenna in [12] is conical while for the proposed LWA in this paper radiation pattern has a half conical shape.

## V. Radiation Pattern Calculation

In the proposed HMSIW structure, the dominant $TE_{10}$ mode is propagating. However, due to the leakage of power, propagation is occurred with attenuation. On the other hand, as illustrated in in Fig. 6, electric field distribution over the dielectric aperture is generated by propagating field inside the waveguide. Thus, filed distribution across the dielectric aperture is similar to the filed distribution related to attenuating $TE_{10}$ mode. In fact, the proposed antenna can be considered as an aperture antenna that an attenuating $TE_{10}$ mode is distributed on its aperture. Consequently, radiated far fields of the antenna can be calculated by Fourier transform of the aperture field.

Based on the above discussion, field distribution across the dielectric aperture can be considered by equation (2).

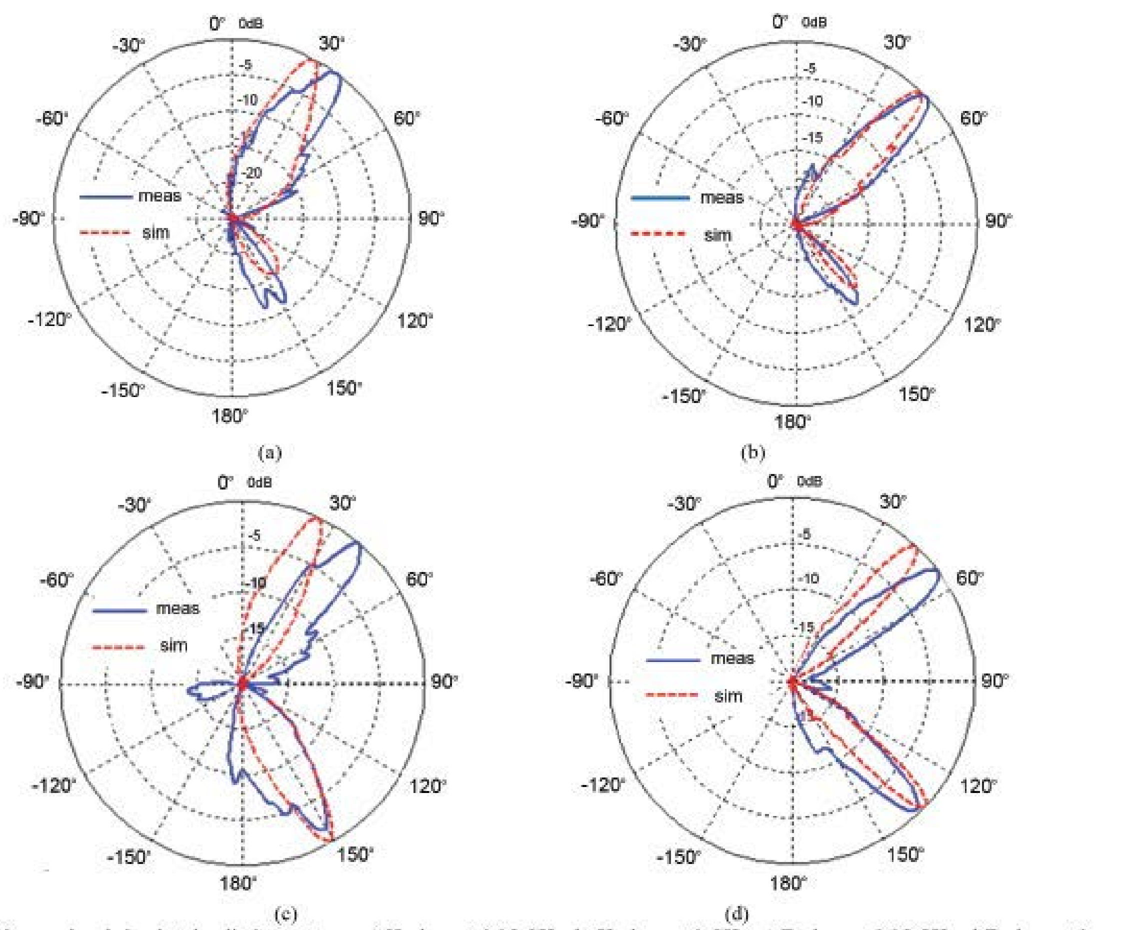
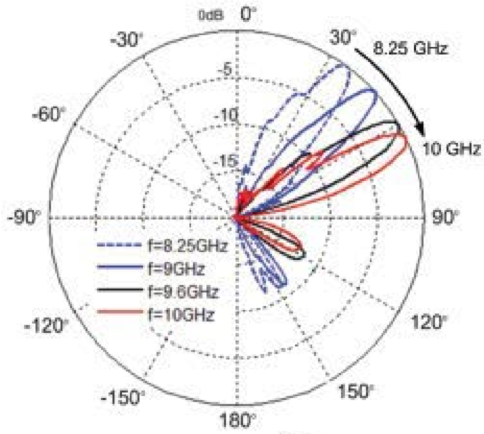



Fig. 8 Measured and simulated radiation patterns: a) H-plane at 8.25 GHz, b) H-plane at 9 GHz, c) E-plane at 8.25 GHz, d)E-plane at 9 GHz



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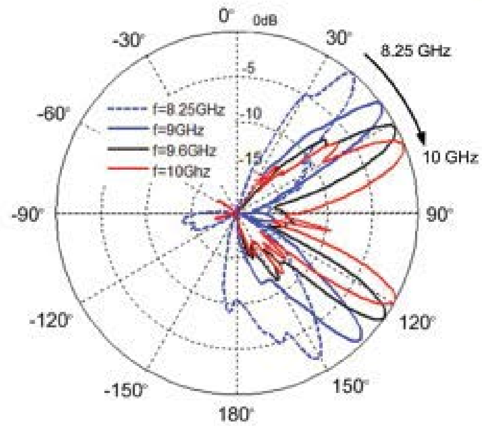


(b)

Fig. 9 Measured radiation patterns of the proposed antenna at different frequencies a) H-plane, b) E-plane

TABLE I. THE EFFECT OF DIELECTRIC APERTURE WIDTH ON THE RADIATION PERFORMANCE OF THE PROPOSED ANTENNA

| $d_1$ (mm) | Bandwidth (GHz) | Fractional bandwidth | Gain (dBi) | Angular coverage | FTBR (dB) |
|---|---|---|---|---|---|
| 0 ([12]) | 8.39~9.07 | 7.8% | 9.1~12.35 | 20° | 0 |
| 6 | 7.97~9.23 | 14.7% | 12.4~16 | 30° | 7.6 ~ 7.8 |
| 10 | 8~9.34 | 15.4% | 12.66~16.34 | 30° | 9.2 ~ 10.3 |
| 15 | 8~9.26 | 14.6% | 13.28~16.32 | 30° | 11.7 ~ 12.8 |

$$E_a = E_o \cos\left(\beta_x x'\right) e^{-\alpha_x x'} \quad (2)$$

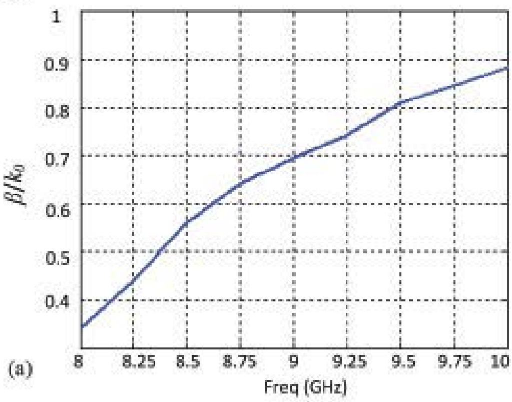
over the aperture

$$0 \le x' \le L_2, \quad -h/2 \le y' \le h/2 \quad (3)$$

where $\alpha_x$ and $\beta_x$ are attenuation and propagation constants which can be determined by simulation. The variations of normalized $\alpha_x$ and $\beta_x$ vs frequency, for the proposed HMSIW structure are shown in Fig. 10, which are obtained by a full wave simulation process using HFSS. In this figure $k_0$ is the wave-number in free space. Considering the equation (2) which describes field distribution across the dielectric aperture and the developed formulations in [13] can be used to calculate far fields and radiation patterns of the proposed antenna. In Fig. 11, the calculated radiation patterns at 8 GHz, 8.5 GHz and 9.2 GHz are illustrated and compared with those obtained by simulation process. Good agreement between calculated and simulated results is observed which proves the validity of the theory used for the calculation of patterns.

## VI. CONCLUSION

In this paper, a leaky wave antenna is proposed using HMSIW technique. The main idea is similar to that presented in [12] but adding an undergrounded dielectric aperture to the proposed structure results in gain and bandwidth enhancement. In addition, the angular region in which the antenna beam steers is also enhanced. A sample antenna is designed, simulated and its radiation characteristics are investigated. The designed antenna is also fabricated using a single layer of printed circuit board (PCB) and its radiation characteristics are measured. Results show that the proposed antenna has the advantages of wide band width, high gain, low fabrication cost and low weight in addition to its common features such as high directivity and beam steering capability. Moreover, the theory for the calculation of radiation pattern for the proposed antenna is presented. In this theory, antenna is considered as an aperture antenna that an attenuated field is distributed across its aperture. Then by Fourier transform of the aperture field, the far fields and radiation patterns are calculated. Good agreement between simulated and calculated results proves the validity of presented theory.



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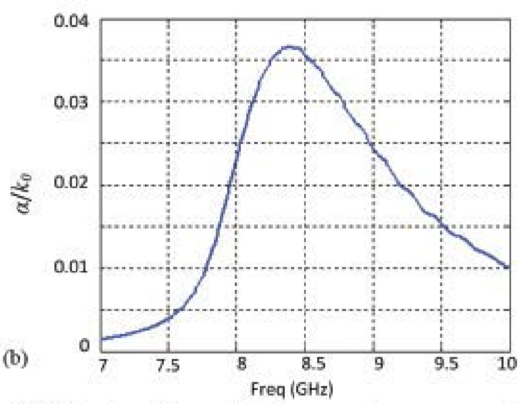
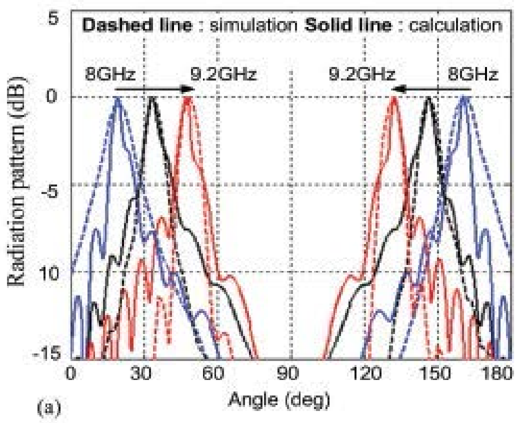


(b)

Fig. 10 Variation of normalized propagation constants of the HMSIW structure versus frequency a) phase constant, b) attenuation constant

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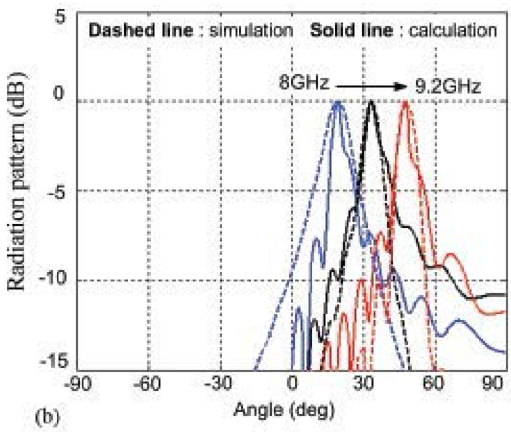


(b)

Fig. 11 Comparison of calculated and simulated radiation patterns: a) E-plane, b) H-plane

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