Dual Image Dielectric Guide (DIDG) for Polarization Diversity Applications at Millimeter Wave Frequency

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Abstract — In this paper, a dual polarized dielectric waveguide is proposed for polarization diversity applications in millimeter wave frequency. The waveguide consists of a squarish dielectric slab attached to two orthogonal vertical and horizontal conductor walls. These walls act as image planes resulting in dual polarized mono-mode region with the same propagation constant for $E_{11}^v$ and $E_{11}^h$ modes. Additionally, two sets of planar transitions exploiting the conductor walls are designed to excite the orthogonal modes as well as provide hybrid circuit integration. The transitions bandwidth (BW) is 3GHz covering 27 to 30 -GHz millimeter wave frequency band. Measured insertion loss of the proposed guide integrated with transition in each side is around 2.7 dB. Isolation between the two orthogonal modes is measured better than 15 dB. Simulated and measured propagation constant of the proposed guide are well-matched.

Keywords — Dual polarized communication, dual polarized dielectric guide, image dielectric waveguide, Millimeter-Wave Communication, polarization diversity.

I. INTRODUCTION

Polarization diversity (PD) is reported as effective diversity for mobile communication system [1]. Despite space diversity, PD results in space and cost efficiency as it doesn’t need physical separation of the antennas. It is applied as a solution for capacity and multipath fading consumption[2]. Moreover, PD reduces the size of MIMO-equipped terminals and base stations [3] as orthogonally polarized antennas have low correlation (even for case they are placed close to each other). Additionally, PD is useful in radar systems [4], fading compensating [5], and dual polarization measurements [6].

With frequency moving toward millimeter-wave (mm-Wave) band, lots of research on DP for MMW frequencies are reported. Some works applied PD on multi-input multi-output (MIMO) systems [7], [8]. Optic and microwave integrated circuits based on a refractive dielectric guide (DG) were emerging in late 20th century [9]. Many efforts were done based on different DG such as image guide [10], rectangular dielectric guide [11], and dielectric slab waveguide [12].

Image dielectric guide (IDG) includes a dielectric strip over a conductor plane as the structure shown in Fig.1.a. An IDG presents low losses at mm-Wave and higher frequencies [13]. The conductor loss is much smaller compared with rectangular waveguide as all sides of the guide are not covered with conductor. Moreover, selecting a proper dielectric constant ratio between the guide and surrounding media (usually air, $\epsilon_0$) will reduce the radiation loss [9]. It can be concluded that the major part of IDG losses at mm-Wave frequencies is its dielectric loss which is depend on the properties of the selected dielectric. In [14], using $E_{11}^v$ instead of $E_{11}^h$ dominant mode is suggested to reduce the conduction loss of the image line. absorption by dielectric material is another source of attenuation in IDG which depends on dielectric’s $\tan\delta$ and dimensions [14].

Despite the advantages of IDG, it can not support both V and H mode simultaneously as there is no mono-mode region for them. In addition to this, there is only one ground plane that can be exploited as a planar transition for only one of the orthogonal polarization. In order to have a transmission proper for dual polarization diversity, a line providing the same propagation constant and cut off frequency for both orthogonal modes (like square DG) is essential. A line which provides physical support of the guide and possibility of two isolated transitions for the two orthogonal modes.

In this paper, a dual polarized dielectric waveguide is proposed for 28 GHz mm-Wave frequency band. The waveguide has a squarish cross-section having two vertical and horizontal conductor walls. The dielectric guide is made from RO4003 (Rogers Co.) having $\epsilon_r = 3.55$. The proposed dual polarized guide is integrated with two planar Microstrip to proposed transitions for orthogonal polarizations. Sec.II presents the principles and design of the proposed guide. The planar transitions are investigated in Sec.III. Sec. IV illustrates the performance of the designed structure. The performance and specification of the dual polarized waveguide make it a good candidate for polarization diversity applications in mm-Wave frequencies on 5G networks.

II. PRINCIPLES OF DUAL IMAGE DIELECTRIC GUIDE

However a dielectric guide (DG) with square cross section have the same cutoff frequency and propagation constant for both V and H modes, it is not physically possible to integrate with planar circuits and excitation (such as microstrip line) as a ground plane or physical support will obstructively perturb the performance of waveguide. The IDG represented in Fig.1.a
overcomes the integration challenge by introducing a ground plane. This plane provides the physical support and can be used for a planar transition.

Figure 2 shows the field distribution inside and around IDG for the \( E_{11}^x \) (called Vertical mode (VM)) and \( E_{11}^y \) (called Horizontal mode (HM)) modes of the IDG having \( \epsilon_r = 3.55 \) and cross section of \( 4.572 \times 2 \times 4.572 \text{mm}^2 \). The VM is mostly centered in the cross section of the IDG close to the ground, while HM’s most strength covers the cross section of the guide but opposite side of the ground plane. Considering \( k_x, k_y, \) and \( k_z \) as propagation constants, receptively, toward \( x, y, \) and \( z \) axis, below equations determine the propagation characteristics of the IDG [15]. The \( \tan^{-1} \) function in Equ.1 must be taken in the first quadrant. one can numerically solve these equations to determine the propagation constant of the IDG toward \( z \) axis (propagation direction).

\[
\begin{align*}
ak_x &= \frac{n\pi}{2} - \tan^{-1}\left(\frac{k_x}{k_{x0}}\right), m = 1, 2, 3,... \quad (1a) \\
bk_y &= \frac{n\pi}{2} - \tan^{-1}\left(\frac{k_y}{\epsilon_{re}(x)k_{y0}}\right), m = 1, 3, 5,... \quad (1b) \\
\end{align*}
\]

where,

\[
k_{x0} = k_{y0} = k^2 - k_0^2, \epsilon_{re}(x) = \epsilon_r - \left(\frac{k_x}{k_0}\right)^2 \quad (2)
\]

An IDG with cross section \( 2a \times b \) in case \( a = b \) to have the same propagation constant, has the same cut off frequency of \( E_{11}^x \) and \( E_{21}^y \). So, there is no region that can support only \( E_{11}^y \) and \( E_{21}^x \) modes. This make the IDG inapplicable for a dual polarized system. Moreover, there is only one conductor wall which can excite only one of the modes.

In order to overcome these challenges and provide planar transition possibility for both modes, dual image dielectric guide (DIDG) is proposed here which is illustrated in Fig.1.b. Two horizontal and vertical conductor planes are attached to a dielectric strip with \( a \times b \) cross-section which \( a = b \) for dual polarized system. This will provide the same propagation constant and cut off frequency for both polarizations. The name dual image comes from the point that the two conductor plans act as two image planes. Additionally, these planes provide the possibility of two orthogonal transitions for the two orthogonal V and H modes. The most important feature of the DIDG is its long mono-mode region for V and H modes. As Fig.3.c presents, the DIDG (having cross sections as \( a \times a \), where \( \epsilon_r = 3.55 \), and \( a = 4.572 \text{mm} \)) provide 7 GHz of mono-mode region for two V and H modes starting from 17.5 GHz to 24 GHz. even for the DG, the length of mono-mode region is 3.5 GHz as can be found in Fig.3.a.

Compare to DG and IDG, the proposed DIDG provides 75% and 50% of size reduction, respectively. This is equal to lower dielectric loss. DIDG will have higher conductor loss compared to IDG as for each polarization a wall is parallel to it resulting in conductor loss. Electric field distribution for the \( E_{11}^x \) and \( E_{11}^y \) modes of the proposed DIDG are illustrated in Fig.2.c and d. The substantially symmetric field distribution for both modes will cause same performance of the X- and Y-polarized modes. The symmetry also provides the possibility of using same microstrip transition design but in orthogonal planes for both polarization as it will be explained more in Sec.III.

III. THE PROPOSED TRANSITION FROM MICROSTRIP TO THE IDIG

Utilizing tapering transition from a dielectric guide to the conventional rectangular waveguide is a simple way to excite a DG and IDG. This method has been used in lots of works based on IDG such as [16]. It’s also exploited in [5] to excite image nonradiative dielectric waveguide. Aperture excitation is reported for Nonradiative dielectric waveguide (NRD) structures in [17]. A planar aperture coupling transition
from planar Microstrip line (ML) to the DIDG proposed in Sec.II is designed in this section. Two sets of feeding slots will be used for V and H modes providing high integration of the DIDG with planar circuits. Compared to tapering, the proposed transition is easier to build, lower cost, more integrable with integrated circuits, and more important, feasible for orthogonal modes excitation.

Figure 4.a shows one side (placed on Horizontal ground) transition from ML to the previously discussed DIDG. Considering the surface current illustrated in Fig.4.b the energy coupling is done through 3 parallel slots (called feeding slots) acting as magnetic dipoles exciting electric fields normal to their axis. This means each set of transitions located on each ground plane will couple the energy from ML to the mode polarized normal to the ML’s ground plane (specified as H and V modes illustrated inset of Fig.5.b).

A conductor wall is attached to the initial side of the DIDG (normal to the orthogonal ground planes and parallel to the feeding slots). This conductor will prevent any leakage from the mentioned side resulting in higher energy transmission toward the other end of the DIDG. Obviously, the distance between the conductor wall and center of the middle feeding slot should be quarter wavelength to have in-phased reflected and transmitted waves. Otherwise, the wave reflected by the wall will weaken or even totally cancel the wave coming through the slots.

Electric field strength around the feeding slots is illustrated inset of Fig. 4.b. The maximum energy concentration is around the 2nd and 3rd slots while the first slot can be considered as a reflector element. The slots approximately quarter wave apart from their neighbour slot(s). Finally, the slots are placed close to the edge of the DIDG where the electric fields are mostly concentrated as shown in Fig. 2. c. and d.

It is noteworthy one-side transition shown in Fig. 4.a is applicable for the case that the DIDG does not need to integrate with planar circuits in both sides such as case DIDG is connected to an dual polarized antenna or is used to excite an DRA array similar to one reported in [16]. In case of providing higher integration ability and measuring the characteristics of the proposed DIDG, dual side transition can be used as illustrated in Fig.5.a where two metallic boxes are used to provide the conductor walls as well as physical support for the circuit. Ports #1 and #2 will support the V-mode while Ports #3 and #4 excite the H-mode of the DIDG. Finally, the general structures of the V and H mode transitions are similar, their dimensions are not exactly same due to isolation and insertion loss optimization.

All of the above make the transition a good candidate to excite a mode normal to its ground while almost no energy is coupled to the orthogonal mode. Simulated S-parameters of dual side transition (shown in Fig.5.a) is illustrated in Fig.5.b showing 1.5 dB of transmission loss ($S_{21}$ and $S_{43}$ related to V and H modes, respectively) and higher than 15 dB of isolation ($S_{31}$ and $S_{41}$). Moreover, transition BW is 27 to 30 GHz covering the MMW band.

IV. EXPERIMENTAL VALIDATION OF THE PROPOSED DIDG

Figure 6 shows the fabricated DIDG and integrated with V- and H-mode transitions. RO4003 substrate ($\epsilon_r = 3.55$) is used to build the DIDG. The horizontal and vertical transitions are made by RO5870 ($\epsilon_r = 3.55$, and $t = 0.254mm$). A TRL kit is used to move the measurement reference point to the one shown in Fig.6(c) to consider the effect of connectors, 50Ω matching and Microstrip bend in Network Analyzer (Anritso MS4647B) calibration. Measured matching and insertion loss of the fabricated structure are presented in Fig.8 showing around 2.7 dB of loss at 29 GHz (center frequency) along with matching better than -10 dB over the BW (28 to 31 GHz). Same results are verified for the HM. However the transitions for both modes are the same, position of the slots are slightly different to optimize the isolation. The propagation constant of the DIDG is measured as illustrated in Fig.7(a) by fabricating two prototypes having different length. The measured constant (same for V- and H-modes) shows a linear behaviour and is in good agreement with the simulated value. Considering the nearly 1.5 GHz frequency shift in measurement results (one can find by comparing the simulated and measure S-parameters), the measured propagation constant is has the same value fin the BW as the simulated value. Finally, Fig.7(b) presents the measured isolation between the V- and H-mode transitions. This graph shows isolation of better than 15 dB between the V- and H-mode ports.

V. DISCUSSION AND CONCLUSIONS

A dual image dielectric guide (DIDG) capable of supporting vertical and horizontal modes was presented in this
Two orthogonal substrates created two ground plane and two orthogonal transitions for V and H modes. The DIDG and transitions were fabricated by RO4003 and RO5870 substrates, respectively. The DIDG and its transitions BD cover 28 to 31 GHz MMW frequency band. Measured insertion loss during operation is linear and in good agreement with simulation. The two sets of transitions provide propagation constant is linear and in good agreement with paper. Additional works are in progress to increase the BW and cover all the mono-mode region.

**References**


