Wideband Dual-mode Dielectric Waveguide with Applications in Millimeter-wave Interconnects and Wireless Links

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Abstract— Millimeter and submillimeter wave dielectric waveguides are receiving increasing attention for high capacity communication links due to the low transmission loss over a large bandwidth. In this paper, a new single-side multi-mode coupler for efficient excitation of two fundamental and polarization-orthogonal modes of a rectangular dielectric waveguide is presented. This technique doubles the available bandwidth of the waveguide without sacrificing the performance The effect of bending the waveguide is also investigated. Finally, the proposed multi-mode coupler is used to feed a high gain dual-polarized dielectric rod antenna. This also doubles the available *wireless* capacity of conventional singlepolarized rod antennas.

1. INTRODUCTION

With the exponential growth in data traffic arising from new subscriptions and emerging web and mobile applications, there is a significant need for efficient and extremely high-throughput wired and wireless links that can provide similar gains in network capacity at all levels. To this end, a substantial improvement in bandwidth and communication energy efficiency is required.

Conventional electrical links, based on TEM waveguide interconnects, are limited to a short range, especially for high-data rate applications. This is mainly due to the fundamental limitations of these links, namely the conductive loss at higher frequencies leading to adverse channel properties, the cross talk and impedance mismatch on these lines [1]. Non-TEM metal interconnects, such as the Substrate Integrated Waveguides (SIW) [2] have been proposed due to superior channel characteristics, but they are still limited to short range applications for high data rates due to the inherent high conductive losses. On the other side of the spectrum, optical links have been extensively used for long-range ultra-high data rate communication and are gradually entering the short/medium range space as well. However system cost and power efficiency of the entire link remain as major obstacles for optical interconnects in the short to medium range ($< 50\,\mathrm{m}$). This is due to the large over-head power consumption in the electro-optic convertors and the high complexity/precision needed for packaging and implementation.

On another front, recent progress in the development of low-power CMOS millimeter/submillimeter wave transceivers opens the way for energy efficient and high throughout links operating in this relatively unexplored frequency range [3]. Coupled with the very low loss characteristics of dielectric waveguides [4], these silicon-based mm-wave transceivers can open the way to a new class of wired links that bridge the gap between conventional TEM electrical interconnects and optical fiber [5–8]. In this paper we introduce a low-loss dual-mode wideband waveguide coupling scheme for the transceiver interface without adding significant packaging complexities.

Millimeter-wave dielectric waveguides have been investigated for the low transmission loss properties that can be exploited as an effective channel in high-speed interconnects [7–9]. In addition to losses, the maximum achievable data-rate in these interconnects is also limited by the dispersive channel characteristics, especially when utilizing a single carrier in order to increase the energy efficiency of the entire system. The available capacity of the waveguide channel can be further boosted by multi-mode excitation of the guide. This enables either higher throughput in the same bandwidth, or, alternatively, the same throughput on a narrower bandwidth that is less affected by the dispersive behavior of the channel. Here, the challenge is the efficient excitation of appropriate modes and polarizations in the waveguides. To this aim, we have recently proposed an all-electrical, low-cost and easy-to-package structure based on millimeter-wave dielectric waveguides for high-throughput interconnects (see Figure 1(a)) [9]. A planar feed structure excites two *polarization-orthogonal* modes of the waveguide, namely the E_x^{11} and E_y^{11} modes (Figure 1(b)). This doubles the available capacity of the waveguide.

In the current paper, we have modified the proposed multi-mode excitation structure to improve the coupling efficiency and further simplify the packaging and implementation. As opposed to the prior work [9], the couplers are now integrated together in a single two-layer PCB placed on one side of the dielectric waveguide (instead of on both sides). This eliminates the routing of the RF

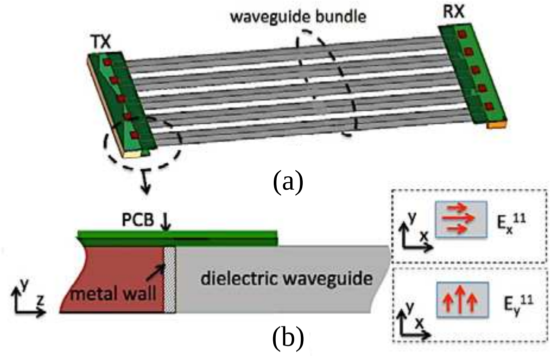

Figure 1: (a) Dielectric waveguide bundle for high-throughput wired links. (b) Conceptual drawing (side view) of the multi-mode excitation structure for a rectangular dielectric waveguide.

signal from transceiver ICs to both printed couplers and then the waveguide. The effect of bending of the waveguide carrying both modes is also investigated. Eventually, the proposed feed structure is also used for realizing a high gain millimeter-wave dielectric rod antenna with dual-polarization, which doubles the capacity for wireless communications.

2. DIELECTRIC WAVEGUIDE CHARACTERISTICS

Dielectric waveguides shaped in rectangular, circular, and hollow circular cross sections have been studied for various applications [4]. They provide a very low insertion loss medium for millimeter/sub-millimeter waves. Due to the recent progress in developing efficient CMOS transceivers at millimeter/sub-millimeter waves, they are receiving increasing attentions for high-speed interconnects.

In [9], we have investigated the *transmission loss* and *bandwidth per pitch* of the rectangular waveguide for different dielectric properties. In rectangular dielectric waveguides, the low permittivity along with the small loss tangent results in a low transmission loss [4, 9]. In this paper, a low-permittivity and mechanically flexible HDPE polyethylene dielectric with $?_r = 2.25$ and $\tan\delta = 0.001$ is used to realize the waveguide ($?_r$ and $\tan\delta$ are measured at 40 GHz using a 900 T model cavity resonator setup made by Damaskos Inc.). The waveguide is designed for operation at the center frequency of 75 GHz. This results in $2.3 \times 2.3\,\mathrm{mm}^2$ waveguide cross-section. Simulations show a transmission loss of 10 dB/m at 75 GHz.

In many applications, mechanically flexible waveguides are desirable to enable effective routing and distribution of a long line. Although the HDPE Polyethylene lines are flexible, the electromagnetic properties of the waveguide at bends should be carefully examined with focus on power leakage and mode conversion. Due to reduced field confinement, the former effect is more severe in waveguides with low permittivity. Figure 2 shows the bending loss of two polarization-orthogonal modes for different bending radii. As expected, the bending loss decreases with increasing the radius or the frequency. The latter is partly due to the fact that at higher frequencies, the effective electrical bending radius is larger (i.e., at higher frequencies the waveguide is effectively closer to a straight waveguide). In addition, at higher frequencies, fields are more confined inside the waveguide. Simulations show that the mode cross-coupling, from one polarization to the other, is less than -40 dB in the entire range for all of the above cases.

3. MULTI-MODE COUPLER

In [9], a printed electric dipole placed on top of the waveguide launches the E_x^{11} mode (with electric field in x direction) into the waveguide. The E_y^{11} mode is coupled into the waveguide using a printed slot dipole placed on the bottom side of the waveguide. In the current paper, to simplify the implementation, the feed structure is modified and both mode couplers are mounted on the single side of the waveguide (see Figure 3(a)). Due to difficulties in co-integration of electric and slot dipoles on a single side, the slot dipole is replaced by a planar horn-like structure realized in a substrate-integrated waveguide (SIW). In addition, a printed Vivaldi antenna, instead of a simple electric dipole, couples the E_x^{11} mode efficiently into the waveguide.

The couplers are made on a two-layer RO3003 PCB ($?_r = 3$, with thicknesses of 100 µm and 150 µm) with three printed metal layers (shown in Figure 3(b), from top M_1, M_2, M_3). As shown

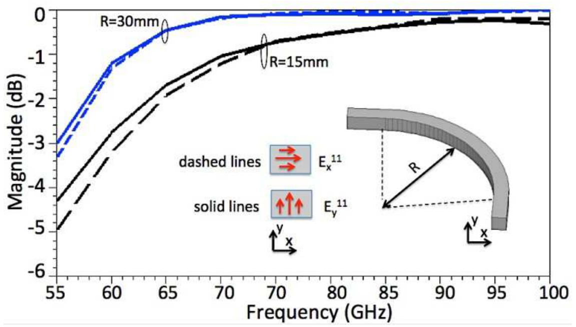

Figure 2: Bending loss of two polarization-orthogonal modes for different bending radii.

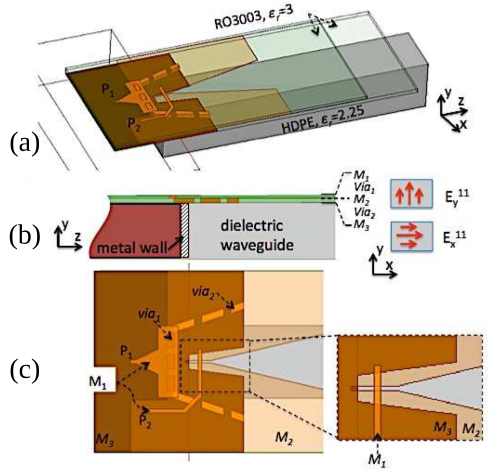

Figure 3: (a) Drawing of the multi-mode excitation structure. P_1 and P_2 launch the fields from *ICs* into E_y^{11} and E_x^{11} modes of the dielectric waveguide. (b) Side view, a two layer RO3003 PCB made of M_1, M_2 and M_3 metal patterns. (c) Top view of the planar multimode excitation structure, Vivaldi antenna realized on M_2 excites the E_x^{11} mode and the SIW horn (between M_2 and M_3) excites the E_y^{11} mode.

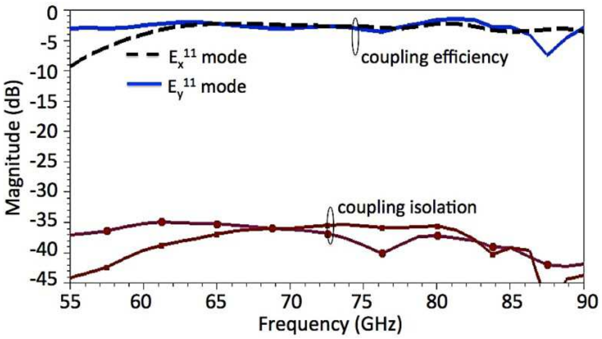

Figure 4: Coupling efficiency of E_y^{11} and E_x^{11} modes and isolation to their unwanted cross-polarized modes.

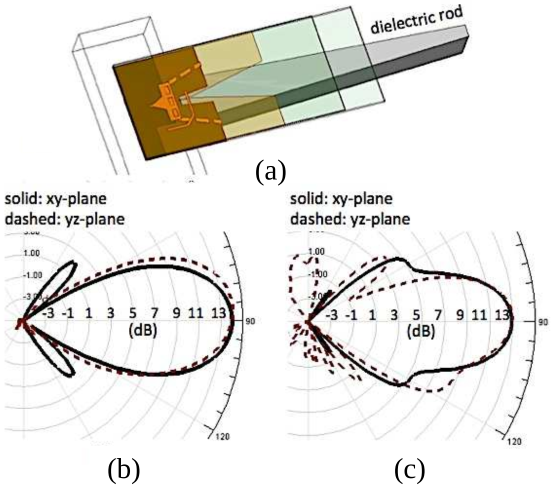

Figure 5: (a) Dual polarize dielectric rod antenna fed by the proposed planar multi-mode coupler. (b) Radiation pattern of the E_x^{11} mode. (c) Radiation pattern of the E_y^{11} mode.

in Figure 3(c), the horn-like SIW is realized by two rows of via_2 connecting M_2 and M_3. The horn-like opening along with tapered opening slot on M_3 gradually couples the TE_{10} mode (with electric field in y direction) of the SIW into the E_y^{11} mode of the dielectric waveguide. These result in a higher coupling efficiency. Eventually, the input of the SIW section (at M_2) is connected to a microstrip transition on M_1 through via_1.

The Vivaldi antenna printed on the M_2 excites the E_x^{11} mode (see Figure 3(c)). Here, the signals with electric field components, mainly in x direction, traveling along the tapered slot on M_2 smoothly and efficiently couple into the E_x^{11} mode of dielectric waveguide. A microstrip line printed on M_1 feeds the Vivaldi antenna.

The coupling efficiency and the amount of leakage to the unwanted cross-polarized mode are plotted in Figure 4. A coupling efficiency of better than 2.5 dB is achieved in the range of 60–

85 GHz. The isolation to the unwanted mode is significant and better than 35 dB for both couplers. A large transmission bandwidth of 50 GHz (2×25 GHz) is available for a single line. When exploited in aggregated lines, the proposed multi-mode waveguide has a great potential for ultra-high throughput interconnects.

The proposed multi-mode feed can be modified to also realize a dual-polarization antenna offering a larger capacity for wireless links. The details are discussed in the next section.

4. DUAL-POLARIZED DIELECTRIC ROD ANTENNA

Dual-polarized antennas, due to the doubling of the available bandwidth, have been extensively used for different applications. Conventional dual-polarized printed antennas such as microstrip patches or electric/slot dipoles offer easy manufacturing and implementation at the expense of a limited gain. Printed Vivaldi antennas, exhibit higher gain, at the expenses of significant difficulties for feeding and implementation for dual-polarization radiation [10]. In this section, employing the proposed planar feed structure based on the dielectric waveguide, we present the dual-polarized rod antenna shown in Figure 5(a). Compared to the printed Vivaldi, the proposed antenna not only exhibits a higher gain but also its implementation and feed network in larger arrays is significantly simplified. The gain of the rod antenna increases with the length of the tapered section [11]. However, due to required mechanical strength, the length is limited to 13 mm. Figures 5(b) and 5(c) show the simulated radiation pattern for both modes. The antenna gain at 75 GHz is 14 dBi and 13 dBi for E_x^{11} and E_y^{11} modes, respectively. The unwanted cross-polarization level for each of modes is less than -40 dB at the maximum directivity.

5. CONCLUSION

A low-cost planar coupler for multi-mode excitation of a rectangular dielectric waveguide is presented. The proposed method boosts the large available bandwidths of dielectric waveguides applicable for ultra-high data rate communication in interconnects and wireless links. Simulations also confirm efficient guiding of the two polarization-orthogonal modes along the waveguide bends.

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