Dual-Channel Half-Mode Substrate-Integrated Waveguide Link Utilizing Mode Division Multiplexing

Mohamed Elsawaf[#1], Constantine Sideris[#2],
[#]Ming Hsieh Department of Electrical and Computer Engineering, University of Southern California, USA
[1]elsawaf@usc.edu, [2]csideris@usc.edu

***Abstract*— This article presents a dual-mode communication link integrated on PCB that utilizes mode division multiplexing between the fundamental and the first higher-order mode of a half-mode substrate-integrated waveguide (HMSIW). The paper introduces methods for selective excitation of both modes. We also demonstrate real-time channel measurements with a pseudo-random binary sequence (PRBS) and a MATLAB simulation of quadrature amplitude (QAM) modulation schemes. To the best of our knowledge, this is the first demonstration of higher-order mode excitation and the first realization of a concurrent dual-mode link on a HMSIW platform. The measured 10-dB return loss bandwidths of the fundamental mode and higher-order mode are 2.6 GHz (12.2-14.8 GHz) and 3 GHz (12-15 GHz) respectively, corresponding to a concurrent bandwidth of 2.6 GHz with less than 200 ps of group delay variation and more than 20 dB of isolation between the channels. The measurement results agree well with the simulation results.**

***Keywords*— half-mode substrate-integrated waveguide (HMSIW), interconnect, multi-mode, multi-channel, wireline.**

I. Introduction

The demand for higher data-rate efficient communication links has necessitated the development of new communication technologies all the way down to the electromagnetics level. The backbone of any communication link is the channel (i.e., the communication medium). Currently, existing guided channels fall into two categories: conventional metallic wires (e.g., microstrip lines and coaxial cables) and optical fibers. Metallic wires form reliable, low-cost channels for short links (tens of cm); however, their excessive losses and dispersion make them unsuitable for high-data-rate applications. On the other hand, optical fibers provide efficient high-speed links for long distances (tens of meters and greater). A "gap" exists between these two technologies due to the inability of either channel type to efficiently support high-data rates for short-range applications: metallic wires fail to achieve these rates due to high losses and limited channel bandwidth and optical links suffer from limited electro-optical conversion efficiency and difficulty of integration with CMOS technology which makes them uneconomical for <10 m long links [1]. To fill this gap in various important applications, such as interrack, interblade, backplane, and interchip communications [2], dielectric and substrate-integrated (SIW) waveguides have been proposed as a potential solution. These guided structures provide readily integrable solutions that support high data rates with acceptable losses and dispersion at relatively low cost.

An SIW is the planar realization of a bulky 3D waveguide inheriting the low-loss capabilities of its bulky counterpart while being readily integrable within standard printed circuit board (PCB) fabrication technologies. The main drawback of an SIW is its relatively large size (half-wavelength). To solve this issue, HMSIW was proposed [3] by removing half of the structure and leaving it open-circuited, thereby eliminating all the odd modes of the SIW. The new structure supports a fundamental mode similar to the full SIW (TE_{10}) with half of the field profile ($TE_{0.50}$). The first higher-order mode of the HMSIW ($TE_{1.50}$) has a field profile that is half of the SIW's TE_{30} mode. Since its introduction, the HMSIW's fundamental mode has been exploited in a plethora of previous work, including mmWave and sub-mmWave applications such as filters [4], power dividers (PD) [5], and antennas [6], [7]. Both SIW and HMSIW have also been successfully applied in THz applications [8]–[10].

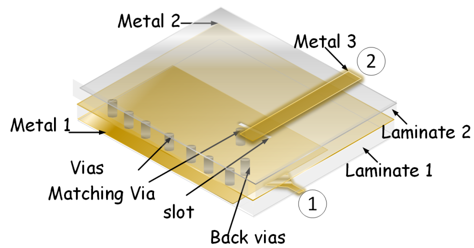


Fig. 1. Layer schematic diagram of the proposed structure.

The HMSIW has better bandwidth (BW) over area efficiency than the SIW; however, since it is an open structure, less isolation is present when bundling (either top/bottom or side by side) multiple guides, requiring additional spacing. This work proposes an approach that leverages concurrent dual-mode multiplexing over HMSIW to increase the BW over area efficiency, doubling the maximum possible data rate by leveraging two modes over the same physical HMSIW with comparable cross-modal isolation to bundling. The gain increases further with bundling, allowing higher data rates. To the best of our knowledge, this is the very first demonstration of exciting and using higher-order modes of a HMSIW.

Higher-order mode excitation has attracted significant attention in SIW designs (e.g., TE_{20} and TE_{30} modes are excited in [11] and [12] respectively). Recently, [13] proposed a design that can excite the fundamental and the first higher-order modes of an SIW to build a multi-mode channel in which the (TE_{10} and TE_{20}) modes are excited over different frequency ranges to achieve frequency/mode division (FDM/MDM) multiplexing. Following this, [14] proposed the

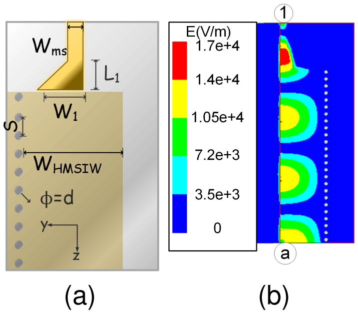


Fig. 2. $TE_{0.50}$ exciting structure (a) Schematic, and (b) Modal Profile.

first concurrent single-band dual-mode link that can fully utilize both (TE_{10} and TE_{20}) of an SIW over 2.2 GHz. The concurrent excitation of both modes is crucial to facilitate transceiver design and allow FDM and MDM to be used separately. In this paper, we propose an excitation technique for the first higher-order mode ($TE_{1.50}$) of an HMSIW using a slot placed at the null position of the mode and a via for matching. It is inspired by the work of [12], which excited the TE_{30} mode of a conventional SIW. It also considers the concurrent matching of both the fundamental and the higher-order modes. This concurrent excitation is then utilized to build a dual-mode channel link half the size of [14] with larger concurrent BW in the same frequency range. The proposed structure has been designed and fabricated using 3-layer PCB technology on Rogers (RT Duroid 5880) laminates with ($h = 0.508$ mm, $\epsilon_r = 2.2$, $tan\delta = 0.004$). A discrete RF transmitter system, excited with a 13 GHz carrier modulated with a PRBS source is built to test the channel. Moreover, a MATLAB (Simulink) model is also developed using the measured S-parameters of the channel to verify higher-order QAM modulation operation. The results demonstrate the utilization of mode division multiplexing to double the data rate over the fabricated HMSIW with low dispersion and significant isolation.

II. Modes Excitation

Fig. 1 shows a schematic diagram of the full proposed structure and its constituent layers. The design is built by stacking two laminates on top of each other. The bottom metal of the top laminate is fully etched out. The SIW is realized in the bottom substrate between metals 1 and 2. The fundamental mode of the SIW is excited by using a tapered microstrip to SIW transition etched in metal 1. The first higher order mode ($TE_{1.50}$) is excited by using a slotline to SIW transition similar to the approach used in [12]. The slotline itself is etched in metal 2 (the top metal of the SIW) and is fed via a microstip to slotline transition (etched on the top metal 3).

A. Fundamental ($TE_{0.50}$) Mode Excitation

The fundamental mode of the HMSIW structure is the $TE_{0.50}$ mode. It is half of the conventional TE_{10} mode. To excite this mode, a field (energy) source should be placed at the center of the guide, and a suitable matching technique should be used to match this source to the guide. Several structures have been investigated to excite and match this mode in the literature [15]–[18]. In this work, the excitation source is a conventional microstrip line, which launches power to the mode maximum location at the center of the SIW. This microstrip is matched to the SIW by adiabatically tapering it (gradual change of impedance) to match its impedance Z_{MS} to the HMSIW's $TE_{0.50}$ modal impedance, $Z_{0.50}$. A 2D schematic of the exciting structure is shown in Fig. 2a. The excitation structure is simulated in ANSYS HFSS with the exciting microstrip (port 1) on one side of the SIW and a terminating waveport (port a) on the other side, as illustrated in Fig. 2b, which shows the modal profile excited by the structure.

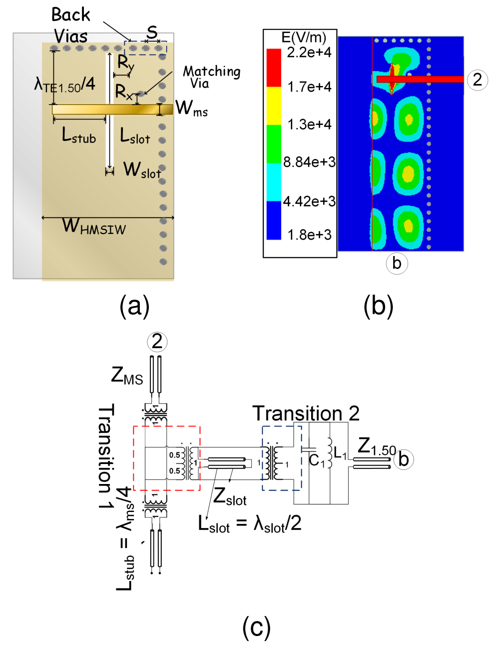


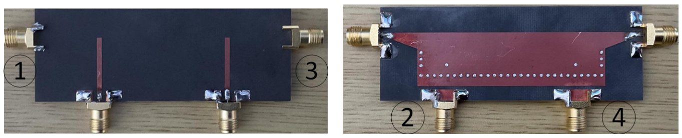
Fig. 3. $TE_{1.50}$ exciting structure (a) Schematic, (b) Modal Profile, and (c) Equivalent circuit model.

B. Higher Order Mode ($TE_{1.50}$) Excitation

The conventional first higher-order mode of the SIW (TE_{20}) does not satisfy the boundary conditions of the HMSIW. Thus, the first higher-order mode is the first higher-order even mode ($TE_{1.50}$), which is half of the (TE_{30}) mode. We propose a method for exciting this mode that utilizes a slotted line etched at the null position of the mode (1/6 of the HMSIW's width) as an excitation source and a via for matching this source impedance to the waveguide. This excitation structure is inspired by the excitation of the SIWs (TE_{30}) proposed in [12]; however, the proposed structure is different in two aspects: it uses a single via for matching and it ensures forward mode propagation not by end launching but by adding reflecting (back) vias spaced at a quarter wavelength from the excitation source as shown in Fig. 3a. The modal profile of the excitation is shown in Fig. 3b.

Table 1. Dimensions of the Proposed Structure

Parameter	Length (mm)	Parameter	Length (mm)
d	1 mm	S	1 mm
L_1	9.2 mm	W_1	6 mm
L_{slot}	6.25 mm	W_{HMSIW}	22 mm
L_{stub}	6.5 mm	W_{ms}	1.6 mm
R_x	3.5 mm	W_{slot}	0.1 mm
R_y	5.5 mm	$\lambda_{TE1.50}$	16 mm



(a) (b)

Fig. 4. Fabricated structure (a) Top, and (b) Bottom sides.

The design starts by selecting the slot dimension to be half-wavelength at the design frequency (center of the working band), followed by adding a via for matching. The via radius and placement are chosen to match the slot impedance to the HMSIW modal impedance ($Z_{1.50}$). The design is based on the circuit model shown in Fig. 3c. The microstrip feeds from port 2 into a resonating slotted line modeled as a short-circuited half-wavelength transmission line [19]. A transformer models the slotted line/waveguide transition, where the imaginary part of the HMSIW impedance is modeled using a capacitor whose value can be extracted from EM simulations at the design frequency. A via is added and modeled as an inductor to match the slotted line into the HMSIW; the inductance value can also be extracted using EM simulation at the design frequency. To concurrently match the two modes, the via is placed at a distance (R_y) greater than (W_1) so as to not affect the excitation of the fundamental mode. Moreover, the back vias are placed 0.2 mm away from the end of the taper (W_1) for the same reason. The dimensions of the exciting structure are reported in Table 1.

III. Experimental Results

The fabricated structure is shown in Fig. 4. The structure is fabricated by stacking two Rogers Duroid 5880 (h = 0.508 mm, $\epsilon_r = 2.2$, $tan\delta = 0.004$) laminates on top of each other using a Rogers 4450 ($h =$ 0.1 mm, $\epsilon_r = 3.2$, $tan\delta = 0.006$) prepreg. The fabricated HMSIW is 5λ (≈80 mm) long, where λ is the cut-off wavelength of $TE_{1.50}$ mode (12 GHz), and the width of the whole structure is 0.25λ. The ports are defined according to Fig. 4, where ports 1 and 3 excite the $TE_{0.50}$ mode and ports 2 and 4 excite the $TE_{1.50}$ mode.

The measured and simulated insertion and return losses of the structure are shown in Fig. 5a, indicating that the return loss (RL) (S_{11}) remains at or below -10 dB between 12.2-14.8 GHz, corresponding to a 2.6 GHz FBW, while that of port 2 ($TE_{1.50}$) is 3 GHz (12-15 GHz) corresponding to concurrent BW of 2.6 GHz for mode division multiplexing (22% of the $TE_{1.50}$ cutoff). The insertion loss of the structure is 1.5 dB for both modes and is very flat across the entire FBW.

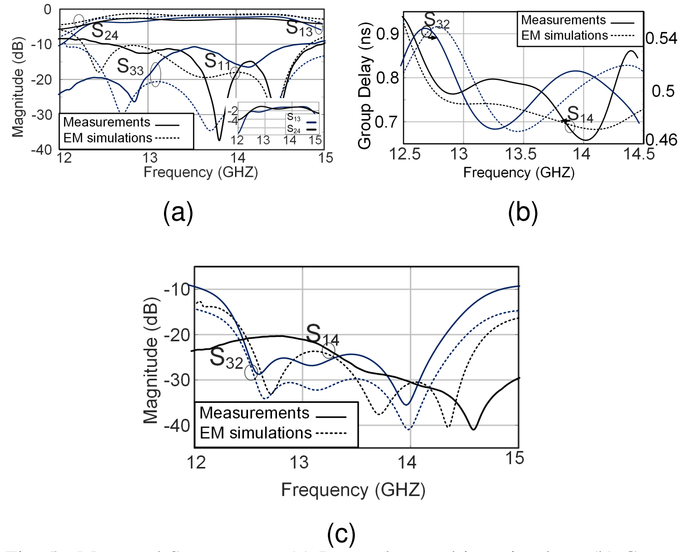


Fig. 5. Measured S-parameters (a) Return loss and insertion loss, (b) Group delay, and (c) Cross-modal Isolation.

Table 2. Comparison against prior work

	[12]	[13]	[14]	**This Work**
Modes excited	TE_{30}	TE_{10} and TE_{20}		$TE_{0.50}$ and $TE_{1.50}$
Frequency-range (GHz)	(7-13)	(10-20)	(10-15)	(12-15)
Technology	SIW			HMSIW
10-dB return-loss FBW[1]	46%	22%	30%	22%
Concurrent return-loss FBW[1]	N/A		2.2 GHz	2.6 GHz
Insertion-loss (dB)	1.5	1	1.5	1.5
Multi-mode coupling (max/min dB)	N/A	(45/5)	(62/40)	(45/15)

Fig. 5b illustrates the group delay variations of both modes; the fundamental mode exhibits only 40 ps of variation across the entire FBW, while the higher order mode exhibits 200 ps of variation. The measured and simulated cross-modal isolation (S_{14}) and (S_{23}) are plotted in Fig. 5c. The isolation remains greater than 20 dB for both modes between 12.5-14.5 GHz.

A discrete RF transmitter is built as shown in Fig. 6a. The system is fed with a PRBS signal at 50 and 100 Mbps (100 Mbps being the maximum achievable by the test equipment) for both channels concurrently, achieving combined data rates of 100 and 200 Mbps across the channel for each case. The measurement setup is shown in Fig. 6b, and the eye diagrams of both channels at both data rates are illustrated in Fig. 6c. A MATLAB model is also built using the measured S-parameters as the channel to illustrate the performance using higher-order modulation. Constellations are shown for both QPSK and 16-QAM in Fig 6d. Table 2 compares this work with previous

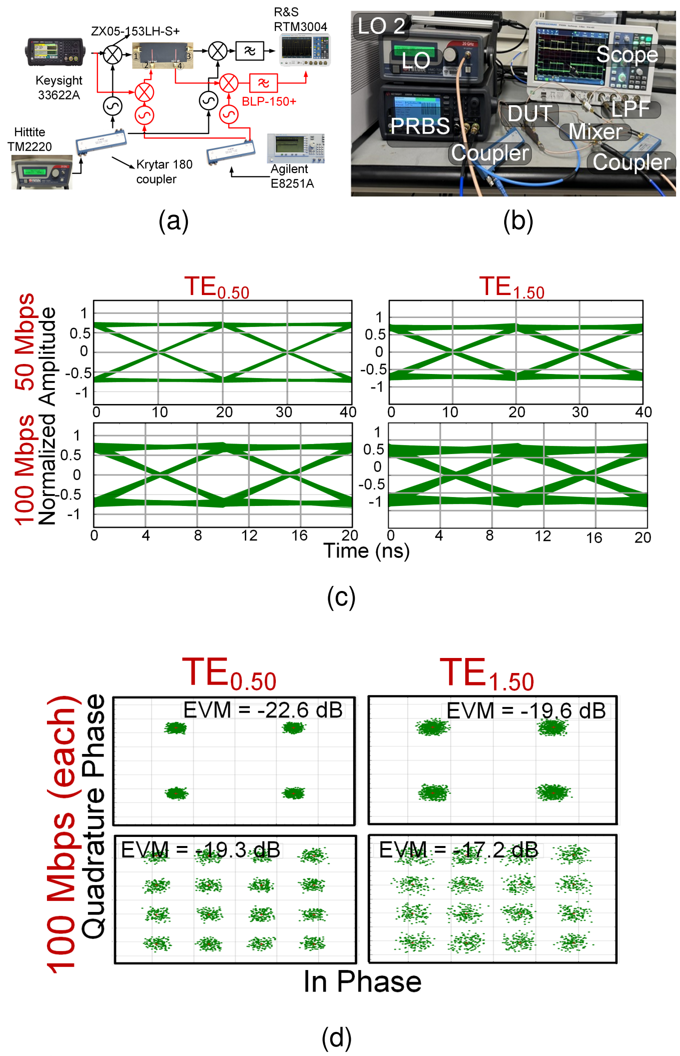


Fig. 6. Real-time channel measurement. (a) Setup Diagram showing $TE_{0.50}$ in black and $TE_{1.50}$ in red, (b) Photo of the setup, (c) Measured eye diagrams, and (d) Simulated EVM of QPSK and 16-QAM.

state-of-the-art works. The present work compares favorably to the previous realizations despite handling the concurrency of the two modes.

IV. Conclusion

This paper demonstrated, for the first time, the concurrent multi-mode excitation of an HMSIW over the same frequency band. This opens the horizon for increasing available communication bandwidth via mode-division multiplexing to increase the channel capacity without requiring increased complexity in transceiver design. The proposed structure efficiently excites the first two modes of the SIW in a 2.6 GHz (12.2-14.8 GHz) band, with a low insertion loss and high cross-modal isolation. The structure has been fabricated, and the measurements agree well with EM simulations.

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