Substrate Integrated Waveguide Mode Coupler for Tracking Applications

Zamzam Kordiboroujeni, Jens Bornemann and Poman P.M. So

Department of Electrical and Computer Engineering, University of Victoria, Victoria, BC, V8W 2Y2, Canada

Abstract — A substrate integrated waveguide (SIW) mode coupler for tracking applications is introduced. The design is based on excitations of TE_{10} and TE_{20} modes for an incoming plane wave. The mode coupler separates the respective mode content and directs their signals to respective output ports. The component is designed to operate at 24.25 GHz with 2.2 GHz bandwidth, using frequency-domain methods (MMT and CST) for design, and a time-domain technique (TLM) for visualization of the electromagnetic fields. A prototype is fabricated on RT/duroid 6002, and measurements agree well with simulations, thus confirming the reliability of the design process.

Index Terms — Substrate integrated waveguide, mode coupler, tracking, frequency-domain techniques, time-domain techniques.

I. Introduction

Over the past decade, substrate integrated waveguide (SIW) circuits have emerged into a mature technology covering passive components, e.g. [1], as well as active device integration, e.g. [2]. As in regular waveguide, higher-order modes can be employed to improve performance compared to all fundamental-mode operation. This concept is regularly used in SIW filters [3]. However, except for the excitation of the next higher-order TE_{20} mode [4, 5], the second SIW mode is hardly ever utilized is SIW components.

Angle diversity systems rely on the reception of at least two modes, one for the signal and the second to track the transmitter. This is based on the fact that when the transmitter is broadside, only the even fundamental mode will be excited whereas for oblique incidence, both even and odd modes propagate [6]. By separating the two modes and monitoring the amplitude of the odd one, a receiver is able to track the transmitter.

A simple mode coupler to separate the two modes has been proposed in planar waveguide circuitry [7]. It is based on a T-junction with matching irises to separate the incoming TE_{10} and TE_{20} modes.

This paper presents such a design in SIW technology. In comparison with [7], the SIW circuit operates at a higher frequency and incorporates a corner such that output ports are accessible at the same substrate interface. Moreover, the matching irises are replaced by individual via holes that can be arbitrarily positioned to achieve appropriate mode coupling. Time-domain simulations and measurements verify the circuit's performance.

II. Design

The design process starts with selecting the substrate as RT/duroid 6002 with ε_r = 2.94, $\tan\delta$ = 0.0012, height of 508 μm, and conductor thickness of 17.5 μm. The via diameter is chosen as d = 0.397 mm (1/64 inch) according to available drill sizes. In order to prevent leakage, the via pitch, p, should be $0.5 < d/p < 0.8$; thus p = 0.6 mm is selected. The fundamental-mode width of the SIW is determined by the cutoff frequency of its equivalent waveguide

$$f_c = \frac{c}{2a_{eq}\sqrt{\varepsilon_r}} \qquad (1)$$

where c is the speed of light, and a_{eq} is the equivalent waveguide width. For operation at 24.25 GHz, f_c = 17.15 GHz, and a_{eq} = 5.096 mm, which leads to a SIW width of a_{SIW} = 5.4 mm [8]. The width of the input port is the SIW equivalent of $2a_{eq}$, which amounts to 10.496 mm.

Fig. 1 shows the layout of the SIW mode converter with equivalent waveguide ports which are used for fast analysis and optimization of the circuit (similar to [9]). Ports 2 and 3 are monomode ports whereas port 1 supports both TE_{10} and TE_{20} modes. Thus the design of the straight waveguide, corner and T-junction sections is straightforward. Only the locations of vias required for better matching have to be optimized so that the TE_{10} mode at port 1 propagates through the circuit to port 2, and the TE_{20} mode at port 1 arrives at port 3.

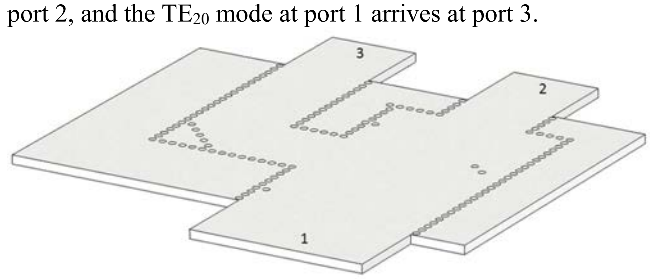


Fig. 1. Substrate integrated waveguide mode coupler with port designations.

Fig. 2 shows a comparison between responses obtained from a mode-matching (MMT) analysis and CST. Excellent agreement is observed of almost the entire band. The results demonstrate that the mode coupler works over a 2.2 GHz bandwidth, centered at 24.25 GHz, where all return loss and isolation values are better than 15 dB. (Note that the mode designation in the inset of Fig. 2 refers to the respective mode at the input port (port 1 in Fig. 1)). In particular, the input

978-1-5090-0698-4/16/$31.00 ©2016 IEEE

return losses of both input modes are acceptable, and the S_{21} and S_{31} parameters demonstrate that the amplitudes of the TE_{10} and TE_{20} modes at the input are indeed coupled to ports 2 and 3, respectively, with an isolation of better than 15 dB between them.

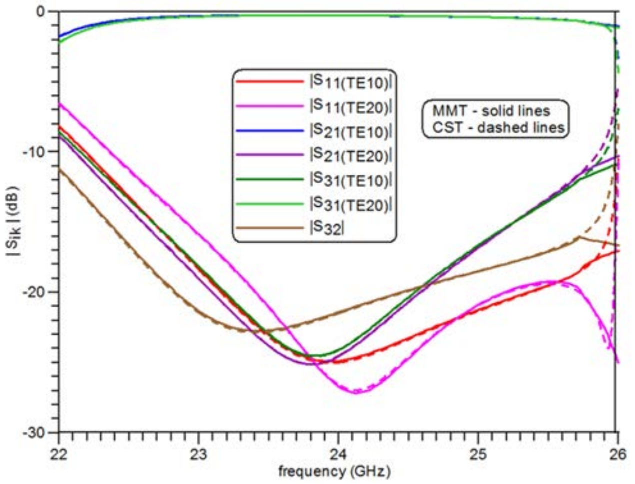
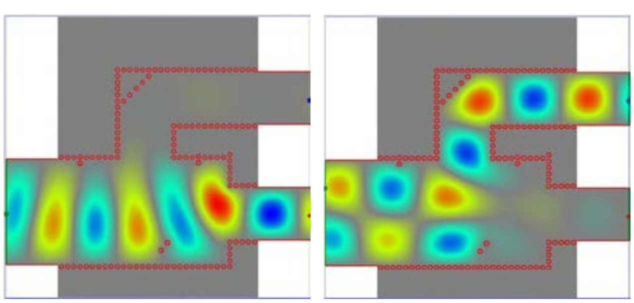


Fig. 2. Performance of SIW mode coupler; comparison between mode matching (MMT) and CST results. Mode designation refers to port 1.

One of the advantages of using time-domain electromagnetics is the ability to visualize the electromagnetic field as it propagates through the circuit. It not only explains how the circuit operates but also why it works and which are the most important parts. Therefore, employing a time-domain transmission-line matrix (TLM) routine similar to [10], snap shots of the fields propagating through the mode coupler when exited with the TE_{10} and TE_{20} modes are shown in Fig. 3a and Fig. 3b, respectively. They demonstrate that the two vias in the lower part of the circuit are instrumental in guiding the field towards the top port when excited with the TE_{20} mode (Fig. 3b). Moreover, this fact is added by the TE_{20} mode being below cutoff in the through port (port 2 in Fig. 1). For excitation with the TE_{10} mode (Fig. 3a), the same vias present only a minor disturbance, and the field can propagate through to port 2.

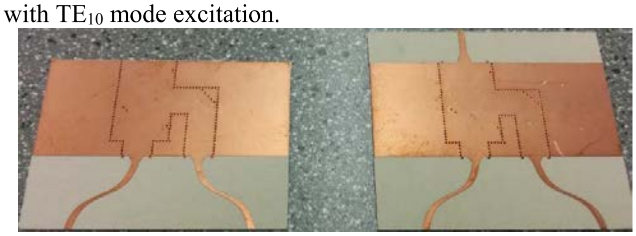


(a) (b)

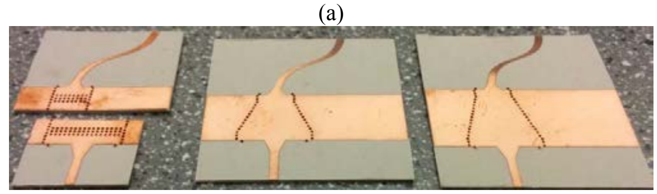
Fig. 3. Plots of electric fields within SIW mode coupler using time-domain simulations with TE_{10}-mode (a) and TE_{20}-mode (b) excitations.

III. Results

The SIW mode coupler has been prototyped, and via-taper transitions [11] as SIW-to-microstrip transitions have been added at all ports as shown in Fig. 4a. Note that the fabricated circuit with transitions at port 1 is necessary to measure the related scattering parameters, while the other one is used for sensitivity measurements. Fig. 4b shows the through-reflect-line (TRL) calibration standards used for the measurements with TE_{10} mode excitation.



(a)



(b)

Fig. 4. Substrate integrated waveguide mode coupler with taper-via SIW-to-microstrip transitions at input/output ports (a); TRL calibration standards for TE_{10} excitation measurement (b).

Fig. 5 shows the measurements in comparison with MMT results that include losses. The measured insertion loss to port 2 (S_{21}) is 0.64 dB compared to computed 0.49 dB. The input return loss (S_{11}) is better than 17 dB over the 2.2 GHz bandwidth at 24.25 GHz. The output return loss at port 2 (S_{22}) is better than 19 dB over the same bandwidth. The return loss at port 3 (S_{33}) deviates from the prediction but is still better than 12.8 dB. We attribute this difference between measurements and calculations to the calibration standards

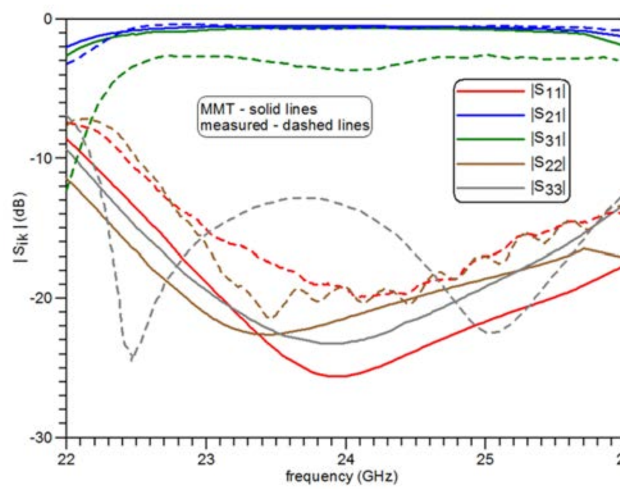


Fig. 5. Comparison between mode matching (MMT) results and measurements.

which involve different widths of input and output ports (Fig. 4b). Moreover, port 1 was not properly terminated but covered with absorbing material to attempt to provide a match for both modes at the input port. Therefore, transmission to port 3 (S_{31}) is measured as -2.8 dB when computations were at -0.63 dB.

In order to measure the sensitivity of the SIW mode coupler with respect to tracking applications, an open K-band waveguide was used to excite the input (Fig. 4a, top left) with a vertically polarized wave coming from different horizontal directions. The output at port 3 was monitored. Compared to a broadside excitation (incoming angle at 0 degrees), the level differences were +6.7 dB and + 7.2 dB at ±10 degrees incoming angle of the wave at the center frequency of 24.25 GHz. That demonstrates that the SIW mode coupler can be used as a tracking device by horizontally moving the component towards minimum output at port 3. Within an SIW system, the input port of the mode coupler will be connected to an SIW horn antenna, e.g. [12], whose feeding waveguide allows propagation of both even and odd modes.

IV. Conclusion

The SIW mode coupler designed for operation at between 23.15 GHz and 25.35 GHz is demonstrated to present a circuit board solution for tracking applications. Although some differences between experimental results and initial performance predictions are observed, the component is well capable of fulfilling its designed task. The importance of individual via holes towards field matching is demonstrated through time-domain simulations that capture the electromagnetic field as it propagates through the component. It is expected that this design will find application in an all-SIW angle diversity front end.

Acknowledgement

The authors acknowledge support for this work from the TELUS Grant in Wireless Communications.

References

[1] M. Bozzi, A. Georgiadis, and K. Wu, “Review of substrate-integrated waveguide circuits and antennas,” *IET Microw. Antennas Propag.,* vol. 5, no. 8, pp. 909-920, June 2011.

[2] F. Taringou, J. Bornemann, and K. Wu, “Broadband coplanar-waveguide and microstrip low-noise amplifier hybrid integrations for K-band substrate integrated waveguide applications on low-permittivity substrate,” *IET Microw. Antennas Propag.*, vol. 8, pp. 99-103, Jan. 2014.

[3] X.-P. Chen and K. Wu, “Substrate integrated waveguide filters: Design techniques and structure innovations,” *IEEE Microw. Mag.*, vol. 15, no. 6, pp. 121-133, Sep./Oct. 2014.

[4] P. Wu, J. Liu, and Q. Xue, “Wideband excitation technology of TE_{20} mode substrate integrated waveguide (SIW) and its applications,” *IEEE Trans. Microw. Theory Tech.*, vol. 63, no. 6, pp. 1863-1874, June 2015.

[5] J. Xu, Z.N. Chen, X. Qing, and W. Hong, “A single-layer SIW slot array antenna with TE_{20} mode,” in *Proc. Asia-Pacific Microw. Conf.*, Melbourne, Australia, Dec. 2011, pp. 1330-1333.

[6] U. Mahr and G. Mörz, “A multimode feed system for angle diversity operation in two polarizations,” in *Proc. 20th Eur. Microw. Conf.*, Budapest, Hungary, Sep. 1990, pp. 1572-1577.

[7] H. Schmiedel and F. Arndt, “Numerical synthesis of simple waveguide mode sensors,” in *Proc. 15th Eur. Microw. Conf.*, Paris, France, Sep. 1985, pp.733-738.

[8] Z. Kordiboroujeni and J. Bornemann, “Designing the width of substrate integrated waveguide structures,” *IEEE Microw. Wireless Compon. Lett.*, vol. 23, pp. 518-520, Oct. 2013.

[9] Z. Kordiboroujeni, J. Bornemann and T. Sieverding, “Mode-matching design of substrate-integrated waveguide couplers,” in *Proc. Asia-Pacific Int. Symp. Electromag. Compat.,* Singapore, May 2012, pp. 701-704.

[10] W.J.R. Hoefer and P.P.M. So, *The Electromagnetic Wave Simulator — A Dynamic Visual Electromagnetics Laboratory Based on the Two-Dimensional TLM Method*, New York: J. Wiley & Sons, 1991.

[11] Z. Kordiboroujeni and J. Bornemann, “New wideband transition from microstrip line to substrate integrated waveguide,” *IEEE Trans. Microw. Theory Tech.*, vol. 62, no.12, pp. 2983-2989, Dec. 2014.

[12] D. Sun, J. Xu, and S. Jiang, “SIW horn antenna built on thin substrate with improved impedance matching,” *IET El. Lett.*, vol. 51, no. 16, pp. 1233-1235, Aug. 2015.