Millimeter Wave Planar Transition from Plastic Rectangular Waveguide to 1 mm Coax

Abstract — This paper reports on a planar transition from 1 mm coax to the fundamental mode of a polystyrene rectangular dielectric waveguide (DWG), covering frequencies from 50 GHz to 85 GHz. Two back-to-back transitions connected by a 12 cm piece of waveguide with tapered points were measured, demonstrating an insertion loss between the microstrip line and the dielectric waveguide of about 2 dB, which agrees well with simulated values.

The structure consists of a 1 mm coaxial board edge connector feeding a microstrip line on a 4 mil thick liquid crystal polymer (LCP) substrate, followed by a vialess transition from microstrip to slotline patterned on the other side of the substrate. The slotline then tapers out and feeds a tapered DWG that is connected to the LCP board by inserting it into a slit along the center of the waveguide.

Index Terms — Dielectric waveguide, millimeter wave technology, wave launcher, packaging

I. INTRODUCTION

Dielectric waveguide (DWG) fabricated from inexpensive plastic has great potential for low-power wired millimeter and submillimeter wave applications [1-2], as well as for metrology applications at submillimeter wave frequencies where rectangular waveguides become prohibitively lossy. For connecting devices that require transmission speeds of more than 10 Gbps over more than 10 m they offer an elegant middle way between wireless links with high gain antennas (cfr. E-band backhaul) and optical fiber transmission. The advantages of plastic DWG are their being metal-free, low-cost, extremely low loss, flexible and that they could be interfaced directly to increasingly cheap CMOS millimeter-wave electronics. Transmitting 60 GHz signals over optical fiber has been demonstrated but this is a costly solution requiring expensive optical modulators and extremely precise alignment of the optical fiber in the package.

A crucial technical challenge that needs to be solved in order to make plastic DWG commercially viable is the interface with planar transmission structures, either on-chip or on-package. Another key technical challenge is the development of waveguide claddings that isolate the plastic fiber from its surroundings. This can be solved using e.g. an expanded Teflon cladding [3], or by using a segmented protective tube [4].

DWG made from inexpensive plastics such as polyethylene or polystyrene have been proposed by a number of authors [5-7]. Transitions from RWG to DWG using a pyramidal horn wave launcher were demonstrated in [5,6] for frequencies up to 300 GHz. Transitions from microstrip and slotline to DWG for E-band were discussed in [7]. These reported transitions show excellent performance with high coupling efficiencies, but are difficult to realize for interfacing to IC's using commercial microwave board technology.

In this paper we present the design, fabrication and measurement of a planar transition from 1 mm coax to a 2x4 mm² polystyrene DWG. The choice for using a 1 mm coaxial board connector was to avoid the use of probes and to demonstrate that the transition could be used as an alternative to 1 mm coaxial cables for e.g. antenna measurements. The prototype also shows that plastic waveguides can be readily integrated with planar circuitry.

The paper is organized as follows: in a first section the construction of the transition is discussed. In a second section, the DWG mode properties are briefly discussed, followed by a third section with design details on the slotline wave launcher and the microstrip to slotline transition. A fourth section then presents measurements on a back-to-back transition and in a final section, conclusions are drawn.

II. MATERIALS AND FABRICATION

Fig. 1 shows the assembled transition. It consists of a U-shaped brass part that was machined to accommodate a 1 mm coaxial board connector from Rosenberger. A 31 x 20 mm² double-sided processed 100 µm LCP board (ULTRALAM® from Rogers) with Cu vias was fabricated and aligned with the connector using alignment dowels on the connector.

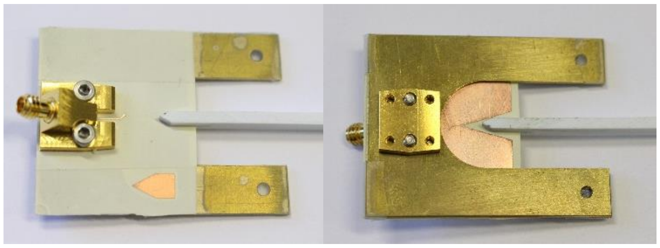

Fig. 1. Photographs of the assembled transition: microstrip side (left) and slotline side (right)

A polystyrene (ε_r = 2.53 and tanδ = 0.0007 [10]) strip (StripStyrene from Evergreen Scale Models) was tapered with an abrasive milling bit on a rotary tool using a brass shaping mold. A fine slit was cut along a short length of the plastic fiber using a laser cutter, then aligned to the LCP board using small Cu markings on the LCP board. The waveguide was not bonded to the board to allow for repositioning during measurement, as will be discussed later.

As most coupling loss occurs as radiation from the slotline coupler, so a closed structure is to be avoided because of parasitic cavity resonances that would occur otherwise.

Therefore, the structure was chosen to be open to the sides and top.

III. MODE ANALYSIS

From literature [8] it is well known that rectangular dielectric waveguides carry two fundamental hybrid modes, termed E_{11}^x and E_{11}^y, with the x,y suffix pertaining to the dominant E field orientation. Both these fundamental modes have no lower cutoff, and have mode field patterns that converge to a plane wave that is lightly bound to the waveguide at the lowest frequencies. At higher frequencies, the field tends to be concentrated mostly in the dielectric, causing an increase in the loss at higher frequencies. The dispersion relations of these modes need to be evaluated numerically, as only approximate closed form expressions exist [8]. For this work, we chose a waveguide cross section covering the 50-110 GHz frequency band, with a guided wave that has most of the guided power inside the dielectric. It was found that a 2x4 mm² cross section of polystyrene would meet this requirement, for which the propagation factors of the fundamental modes are shown in Fig. 1 below. To illustrate the frequency dependence of the mode field distribution, the fundamental mode patterns at 40 GHz and 100 GHz are included as insets.

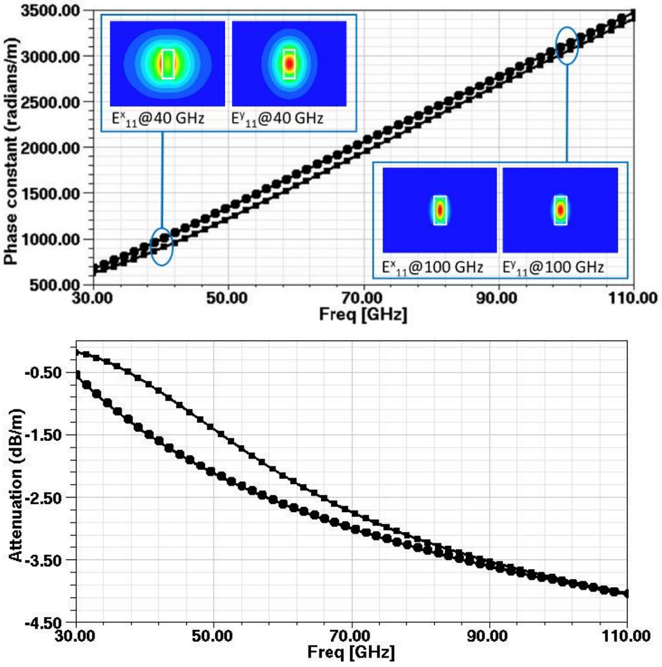

Fig. 2. Propagation constants of the fundamental E^x (squares) and E^y (rectangles) modes: imaginary part (top) and real part (bottom) for a 2 x 4 mm² polystyrene guide. Scalar field plots at 40 GHz and 100 GHz for the two modes are included as insets.

When choosing which of the two fundamental modes to couple, a compromise is needed between propagation loss, potential higher order mode excitation and proneness to bending loss through radiation. As can be seen from Fig. 2, the E_{11}^y mode has slightly lower loss, but on the other hand the higher order mode cut-off frequency of the E_{12}^x mode is higher than that of the E_{12}^y mode. In addition, bending loss will be less severe for the E_{11}^x mode which has its field more confined to the dielectric.

IV. TRANSITION DESIGN

Transitioning the coaxial mode to the DWG mode is done via microstrip and slotline as intermediate transmission structures, as shown in Fig. 3. A broadband transition from microstrip to slotline is realized using the technique discussed in [9]. A circular microstrip pad of diameter 0.46 mm is combined with a circular slot with diameter 0.24 mm that are offset by the dimensions b and c as shown in Fig. 3. The smallest slotline width was taken to be 0.1 mm in order to minimize radiation at this point. Only towards the transition to DWG was the slotline tapered out further.

The waveguide launching structure itself is a more refined version of one of the structures in [7], where the additional waveguide tapering of the DWG allows are more gradual transformation of the slotline mode as it “radiates” into the waveguide. This tapering was found to considerably enhance the coupling efficiency compared to the case of a flat headed DWG. Further optimization of the waveguide end is certainly possible, but for this work we limited ourselves to a taper that could be realized with some precision by manually shaping the tip using a rotary tool and a brass shaping mold.

The design and optimization of the transitions from microstrip to slotline and slotline to DWG were done separately in HFSS v15 with an intermediate reference plane at the widest end of the slotline taper (W_{slot}), before it tapers out further out to the DWG. The layout parameters are shown in Fig. 3 with the optimized values given in the figure caption.

A row of grounding vias is used to make sure the body of the connector is well connected to the microstrip ground plane.

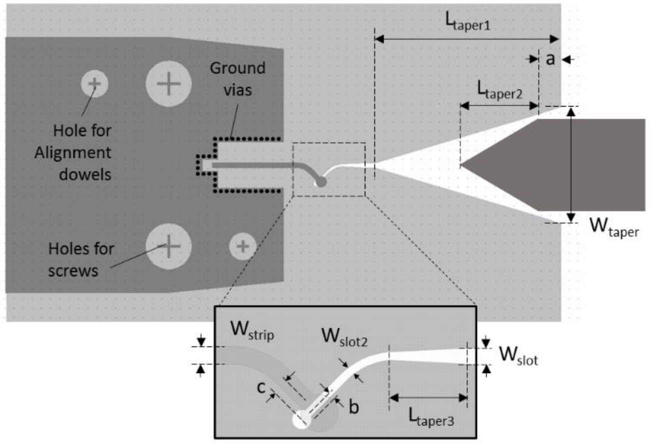

Fig. 3. Layout of the transition from microstrip to DWG via an intermediate (tapered) slotline, including the footprint of the 1 mm coaxial board connector: L_{taper1} = 4 mm, L_{taper2} = 1.8 mm, L_{taper3} = 1.5

mm, W_{taper} = 3 mm, W_{strip} = 0.22 mm, W_{slot} = 0.2 mm, W_{slot2} = 0.1 mm, a = 1.2 mm, b = 0.1 mm, c = 0.21 mm.

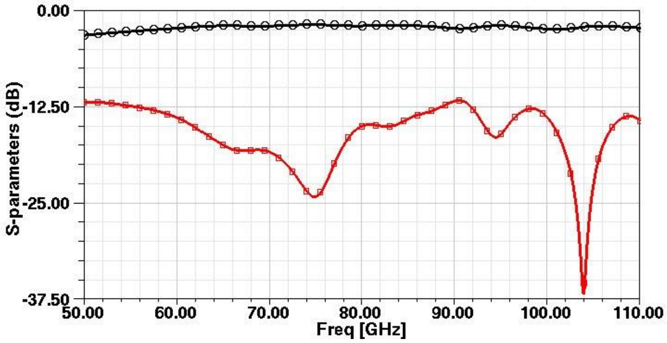

Fig. 4. Simulated S-parameters for the optimized slotline to DWG transition: S_{11} in red, S_{21} in black

V. EXPERIMENTAL RESULTS

Two transitions were fabricated and assembled back-to-back with a 12 cm long polystyrene strip. Measurements were performed using a 110 GHz vector network analyzer set-up which was calibrated at the 1 mm test ports. The setup is shown in Fig. 5. The connectors were tightly fastened to the test ports, allowing the position of the DWG relative to each of the LCP boards to be tuned during measurement. In this way, optimal alignment could be achieved. The measured S-parameters for this optimal alignment between 30 and 110 GHz are shown in Fig. 6. It is worthwhile to note that the alignment of the waveguide was not found to be very critical.

Fig. 5. Measurement setup

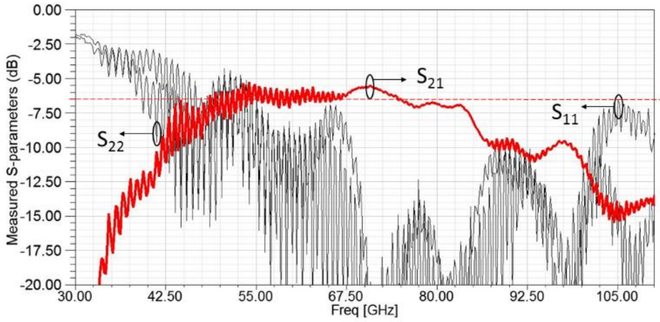

Fig. 6. Measured S-parameters of a back-to-back connection of two coax to DWG transitions and a 12 cm polystyrene strip.

The measurements show that single mode propagation is achieved up to about 85 GHz, after which the transition seems to suffer from additional radiation loss and/or higher mode excitation. To *estimate* the insertion loss of a single transition from microstrip to DWG, we can take the value of S_{21}, subtract 0.5 dB on each side for the connector (as specified by the manufacturer) and subtract the attenuation loss of the length of waveguide between the reference planes used in the simulation. The result is about 2 dB of insertion loss per transition, which agrees well to simulation. To characterize the transition rigorously, we will fabricate multiple sections of waveguide with different length, in addition to an open ended waveguide on each side. This will allow us to use a thru-reflect-line (TRL) de-embedding procedure to determine both the waveguide attenuation and the S-parameters of the transition. More precise fabrication of the waveguide and improved alignment of the waveguide to the transition will be needed since the TRL procedure assumes the embedding error boxes to be identical between the three structures.

VI. CONCLUSIONS

In this paper, we presented the design and measurement of a planar transition from 1 mm coax to a rectangular 2x4 mm² polystyrene waveguide. The insertion loss per transition was found to be around 2 dB in the 50 to 85 GHz range by measuring two back-to-back transitions connected by a 12 cm polystyrene strip.

REFERENCES

[1] S. Fukuda et al., “A 12.5+12.5 Gb/s Full-duplex Plastic Waveguide Interconnect,” *IEEE Journal of Solid-State Circuits*, Vol. 46, No. 12, pp. 3113 – 3125, Dec. 2011.

[2] W. Volkaerts et al., “An FSK plastic waveguide communication link in 40nm CMOS”, *ISSCC*, San Francisco, USA, Feb. 2015.

[3] J.A. Walter, “A Dielectric waveguide having higher order mode suppression”. U.S. Patent 4 875 026, Oct. 17, 1989.

[4] H.-U. Nickel et al., "Novel flexible dielectric waveguide for millimeter and sub-millimeter frequencies — Design and characterization," *ARFTG 2014*, 4-5 Dec. 2014.

[5] A. Hofmann et al., "Flexible Low-Loss Dielectric Waveguides for THz Frequencies with Transitions to Metal Waveguides," *Proc. European Microwave Conference*, pp. 955 – 958, Oct. 2003.

[6] J. Weinzierl, C. Fluhrer, H. Brand, "Dielectric Waveguides at Submillimeter Wavelengths", *Proc. IEEE International Conference on Terahertz Electronics*, pp.166 – 169, Sep. 1998.

[7] J. Richter et al., "A Broadband Transition Between Dielectric and Planar Waveguides at Millimeterwave Frequencies," *Proc. European Microwave Conference*, pp. 947 – 950, Oct. 2003.

[8] C. Yeh and F. Shimabukuro, *The Essence of Dielectric Waveguides*, Springer, 2008.

[9] B. Shuppert, "Microstrip/slotline Transitions: Modeling and Experimental Investigation," *IEEE T-MTT*, Vol.36, No.8, pp.1272-1282, Aug 1988.

[10] C.A. Balanis, “Measurements of Dielectric constants and Loss Tangents at E-band Using a Fabry-Pérot Interferometer”, Langley Research Center, Hampton, VA, NASA TN D-5583, Dec. 1969.