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Structured-Glass Waveguides (SGW) and TRL Calibration Standards

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Abstract—In this work, W-band waveguide channels are characterized for the first time in structured-glass waveguide technology to demonstrate the technology’s low-loss capabilities, while at the same time, TRL calibration standards are developed to coincide with the waveguide characterization for expression of highly accurate measured results. Both the waveguides and calibration standards are realized using three glass wafers in a double H-plane split format with near-vertical laser-induced structured-glass sidewalls. The measured insertion loss per unit length is determined to be in the range of 0.0109 to 0.0230 dB/mm and remain stable over the 75 to 110 GHz range with a return loss that is better than 20 dB. This work represents excellent attenuation measurements (dB/mm) and marks the first characterizations of SWG lines and calibration standards in order to promote further investigations for use in future millimetre and sub-millimetre wave applications.

Keywords—Calibration standards, E-plane transitions, laser-induced micromachining, structured glass, SGW, transmission line, TRL calibration, waveguide technology.

I. INTRODUCTION

Investigation of the millimetre and sub-millimeter wave regions of the electromagnetic spectrum can harbour many new stems of research and applied science in fields such as medical imaging, high-data rate communication, cosmology and spectroscopy. These fields have direct and desirable applications, however, technological fields that can enable this research must evolve and take on new perspectives in order to meet the high-performance requirements of the aforementioned disciplines. Work in the millimetre-wave regions have been dominated by computer numerical control (CNC) milling, deep reactive ion etching (DRIE) of silicon wafers, or SU-8 photo-resist micromachining, each of which has demonstrated varying results when applied to waveguide-based passive components. Albeit, in [1], a novel structured-glass waveguide (SGW) technology was demonstrated as a candidate for achieving high-performance and batch-producible components, where an 88 GHz filter was demonstrated with remarkable accuracy. This accuracy was enabled by the fabrication process and allows for vertical sidewalls to be produced, and ultimately, overcomes the issues of sidewall under-etching and scalloping as indicated in technologies such as DRIE. However, at the time, structured-glass calibration standards were not available and the component was demonstrated as a *filter component package* that included a metallic split-block interface and E-plane feeding transitions.

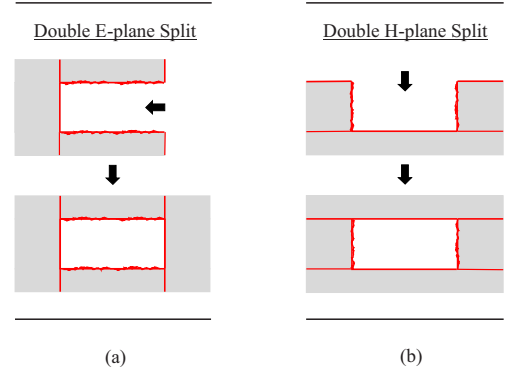


Fig. 1. End-view of a double E-plane split (a) and a double H-plane split (b) used in three-layer wafer fabrication. (Adapted from [1]).

In this work, we demonstrate the development of a structured-glass waveguide transmission line and the associated Thru-Reflect-Line (TRL) calibration standards in order to further characterize structured-glass waveguide technology for high-performance millimetre-wave applications. The TRL calibration standards are utilized in order to take high-precision measurements of a 14 mm long WR-10 line produced in a double H-plane split format. The characterization of the calibrated transmission line gives insight to the potential of the technology and demonstrates a very low-loss waveguide component that is highly competitive to other existing technologies. In addition, a sample comparison of technologies are tabulated in order to compare and contrast the results of other state-of-the-art technologies within the millimetre-wave region.

II. STRUCTURED-GLASS COMPONENT DESIGN

A. Waveguide and E-plane Transitions

The waveguide transmission line is designed in the form of a standard WR-10 waveguide by using three structured-glass wafers in a double H-plane split format. Fig. 1(b) depicts the layout of the H-plane split and is contrasted from the potential double E-plane split shown in Fig. 1(a). The thickness of the middle wafer is selected in order to replicate the height of a WR-10 waveguide channel at 1.27 mm. In this manner, the height of the middle glass wafer is minimized and also maintains a lower aspect ratio than would be required of the double E-plane split. This wafer thickness is specified as 1.267 mm, where an additional 3 μm is accounted for

in the subsequent metallization procedure. The channel of the WR-10 transmission line is shown in Fig. 2, which further depicts the general assembly of three wafer chips. The transmission line section for measurement is specified as 14 mm. Similar to the feeding mechanism described in [1], the structured-glass component is held in a metallic split-block interface that houses UG-387/U waveguide flanges and feed the E-plane port transitions that are micromachined in the top wafer (cover) layer. In this work, wideband E-plane transitions are developed to feed the waveguide structure and reduce reflections throughout the frequency region of interest. These transitions are to be calibrated out during measurement in order to accurately measure the transmission loss and return loss of the structured-glass transmission line. A description of the E-plane transitions are shown in Fig. 3. The simulated results for an E-plane transition and its associated feed-lines are given in Fig. 4 over the full W-band range (75 to 110 GHz).

B. TRL Calibration Standards

In order to characterize the transmission line from Section IIA in structured-glass technology, glass-based TRL calibration standards were designed. Each of the components are defined with equivalent split-block interfaces and E-plane transitions which feed the *thru*, *reflect*, and *line* components. The *line* calibration length is set to $\lambda/4$ of the guided wavelength for the frequency of interest (i.e., 88 GHz for future earth observation). In this manner, the effects of the split-block interface and E-plane transitions that feed the device-under-test (DUT) can be accounted for in the measurement setup and allow for a precise characterization of the transmission and reflection coefficients of the 14 mm waveguide line described in Fig. 2. Each of the TRL components are represented in the top-right of Fig. 3 in a vacuum-shell view where the input feed positions are outlined by the E-plane port transitions. Three individual split-block interfaces were created to house each of the calibration standards and allow for them to be used again in future W-band SGW measurements as a custom calibration set.

III. FABRICATION AND MEASUREMENTS

For the WR-10 waveguide and the associated TRL calibration standards, three Borofloat 33[®] wafers were produced using the Flexinity[®] process [2]. Following the method described in [1], each of the components is sputtered with gold (Au) in order to metallize both sides of the wafer chips with a conductive layer. A thin chromium (Cr) layer was applied prior to the conductive layer for proper adhesion. Each of the waveguide sidewalls have been widened by $1.5 \mu\text{m}$ to account for metallization. This step helps to mitigate any offset or deviation from the desired frequencies of interest; no side-wall under-etching effect is compensated for in the design. Alignment of the three wafers is conducted using high-precision alignment pins before the final thermo-compression bonding steps takes place.

Once assembled, the WR-10 waveguide was placed in its own split-block interface and tested using a Rohde & Schwarz ZVA24 with W-band up-converters. The newly designated

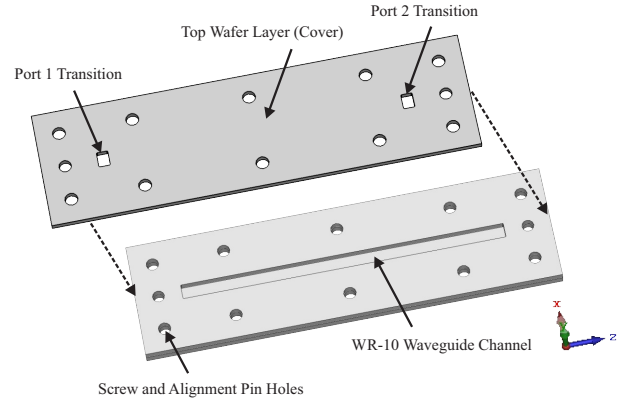


Fig. 2. CAD assembly of the 14 mm WR-10 transmission line composed of three structured-glass wafer layers.

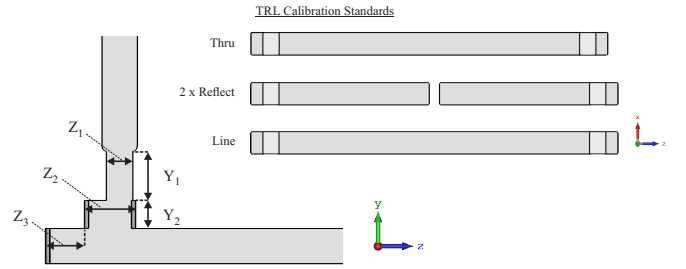


Fig. 3. CAD side view of the E-plane transition (left) and a top view of the TRL calibrations standards (right). The dimensions of the E-plane transition are $Y_1 = 1747 \mu\text{m}$, $Y_2 = 1000 \mu\text{m}$, $Z_1 = 956 \mu\text{m}$, $Z_2 = 1838 \mu\text{m}$, and $Z_3 = 1389 \mu\text{m}$. The overall lengths of the TRL standards are: *thru* = 40.403 mm, a single *reflect* = 20.203 mm (note that two reflect sections are defined on a chip back-to-back), and *line* = 41.553 mm. The waveguide height and width dimensions are taken as standard WR-10 (1.27 mm x 2.54 mm).

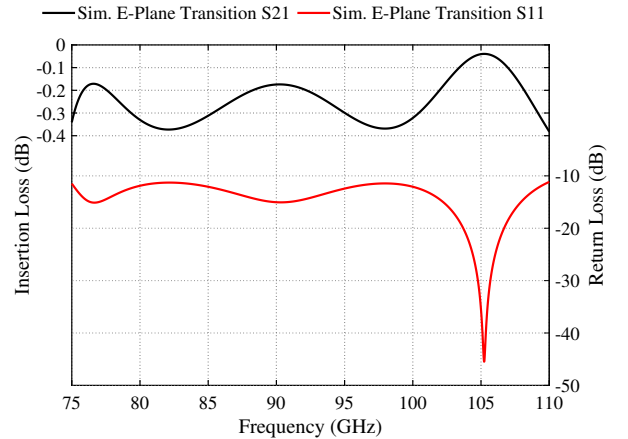


Fig. 4. Simulated S-parameter results of an E-plane transition and associated feed-lines. Equivalent conductivity simulated as 45.61 MS/m.

SGW-TRL standards were used for calibration in order to compensate the effects of the brass split-block interface as well as the E-plane transitions that feed the 14 mm waveguide line. Fig. 5(a) presents the middle layer of the 14 mm line length chip before metallization, Fig. 5(b) depicts the middle layer of a gold (Au) coated *reflect* calibration chip before assembly, and Fig. 5(c) depicts a DUT connected to WR-10 waveguide

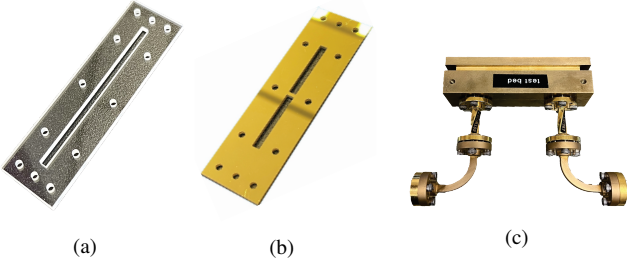


Fig. 5. Fabricated samples and prototype measurement. (a) The middle layer of a 14 mm test line (bare structured glass on a black textured background), (b) the middle layer of an Au-coated reflect calibration standard (two reflect standards are defined on the chip back-to-back), and (c) a fully assembled component held in its metallic interface during measurement.

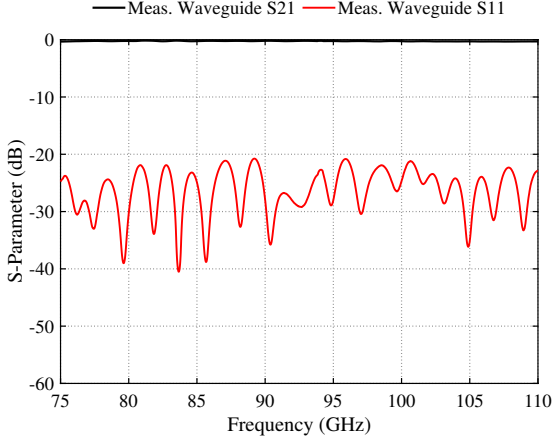


Fig. 6. Measured S-parameter results of the 14 mm SGW line after TRL calibration.

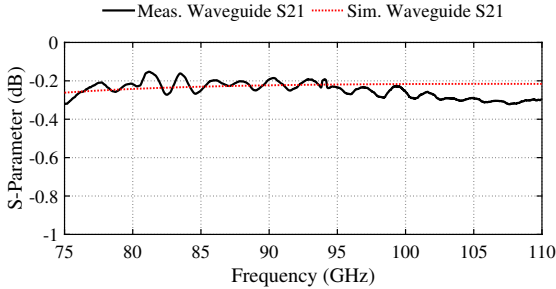


Fig. 7. Close-up view of the measured insertion loss of the 14 mm SGW line after TRL calibration. The theoretical WR-10 waveguide (Sim) is modelled with a conductivity of 24.0 MS/m and surface roughness of 1 μm in CST Microwave Studio.

lines for final measurement. Once the network analyser was calibrated using the newly designed SWG-TRL kit, the 14 mm waveguide S-parameters were measured; Fig. 6 presents the measured results over the full W-band region. The measured return loss is better than 20 dB throughout the full frequency band, while the measured insertion loss is in the range of approximately 0.153 to 0.322 dB. Fig. 7 presents a close-up view of the insertion loss with a comparison to a simulated WR-10 waveguide structure with a conductivity of 24.0 MS/m and surface roughness of 1 μm . Curve smoothing (averaging) has been applied to reduce the noise of the measurements.

Table I provides an extensive sample comparison to different technologies that are either commercially available

Table 1. Sample Comparison of State-of-the-Art Waveguide Technologies.

Technol.	Manuf. Profile	f_o (GHz)	Attenuation [†] (dB/mm)	Ref.
CPP [‡]	Monoblock	75 – 110	0.00328	[3]
CNC	NA	220 – 330	0.04	[4]
DFP	E (GGW)	220 – 330	0.02 – 0.07	[5]
DMLS	Monoblock	75 – 110	0.0103	[6]
DRIE	Double H	110 – 170	0.008 – 0.016	[7]
DRIE	Double H	220 – 325	0.02 – 0.07	[8]
HE	Single H	75 – 110	0.0276	[9]
MLS	Monoblock	140 – 220	0.09	[10]
MLW	Multi H (EBG)	110 – 170	0.02	[11]
MMAM	Multi H	220 – 325	0.06 – 0.122	[12]
SLA ^{††}	Monoblock	60 – 90	0.03 – 0.06	[13]
SLA	Single E	75 – 110	0.011	[14]
SLA	Monoblock	75 – 110	0.0055	[6]
SLM	Monoblock	60 – 90	0.00751	[15]
SLM	Monoblock	110 – 170	0.01896	[15]
SLM	Monoblock	75 – 110	0.0304	[16]
SPR	Monoblock	75 – 110	0.010	[17]
SU-8	Multi H	140 – 170	0.011	[18]
SGW	Double H	75 – 110	0.0109 – 0.0230	T.W.

CNC = Computer-numerical control, CPP = Commercially produced product, DFP = Dry-film photoresist, DMLS = Direct metal laser sintering, DRIE = Deep reactive ion etching, EBG = Electromagnetic bandgap, GGW = Groove-gap waveguide, HE = Hot embossing, MLS = Micro-laser sintering, MMAM = Micro metal additive manufacturing, MLW = Multi-layer waveguide, NA = Not available, SLA = Stereolithography, SLM = Selective laser melting, SPR = Screen-printing, SU-8 = Photo-resist, [†] = Values that are not reported as a range are reported as average, at center frequency, or ‘as achieved’, ^{††} = Ceramic-mixture stereolithography, [‡] = Commercial; instrumentation grade from Pasternack.

or have been reported in the literature at similar frequency bands. A wide range of technologies are compared and represent a varying degree of results. On comparison of the different measured technologies, the SGW demonstrates a highly competitive result that is able to contend with state-of-the-art technologies. Notably, the measured results of this experiment remain highly stable over the frequency region of interest as demonstrated in Fig. 6 and Fig. 7.

IV. CONCLUSION

In this work, waveguide transmission lines are characterized for the first time in structured-glass waveguide (SGW) technology. In addition, custom TRL calibration standards are developed to coincide with the waveguide characterization in order to achieve accurate measurement results which further demonstrate the low-loss capabilities of the technology. The components are realized using three glass wafers in a double H-plane split format. The measured insertion loss per unit length is shown to be on the range of approximately 0.0109 to 0.0230 dB/mm throughout the W-band region. The introduction of the low-loss capabilities of SGW components into the literature highlights its considerable potential for future millimetre-wave components and candidacy for commercial adoption.

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REFERENCES

- [1] C. Bartlett, A. Malavé, M. Letz, and M. Höft, "Structured-glass waveguide technology for high-performance millimetre wave components and subsystems," *IEEE J. Microw.*, vol. 2, no. 2, pp. 307-315, Apr. 2022.
- [2] Schott Ag, "Glass Made of Ideas" - Flexinity, Schott.com. [Online]. Available: <https://www.schott.com/de-de/products/flexinity-p1000320>, accessed: 01-03-2022.
- [3] Pasternack Enterprises Inc., "WR-10 instrumentation grade straight waveguide section 3 inch length, UG-387/U-Mod round cover flange from 75 GHz to 110 GHz," [Online]. Available: <https://www.pasternack.com/images/ProductPDF/PEW10S010-6.pdf> [Accessed 10 Feb 2023].
- [4] J.-Q. Ding, S.-C. Shi, K. Zhou, Y. Zhao, D. Liu and W. Wu, "WR-3 band quasi-elliptical waveguide filters using higher order mode resonances," *IEEE Trans. THz Sci. Technol.*, vol. 7, no. 3, pp. 302-309, May 2017.
- [5] S. Farjana, M. Ghaderi, A. U. Zaman, S. Rahiminejad, P. Lundgren and P. Enoksson, "Low-loss gap waveguide transmission line and transitions at 220–320 GHz using dry film micromachining," *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 11, no. 11, pp. 2012-2021, Nov. 2021.
- [6] S. Verploegh, M. Coffey, E. Grossman and Z. Popović, "Properties of 50–110-GHz waveguide components fabricated by metal additive manufacturing," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 12, pp. 5144-5153, Dec. 2017.
- [7] J. Campion et al., "An ultra low-loss silicon-micromachined waveguide filter for D-band telecommunication applications," *Proc. IEEE/MTT-S Int. Microw. Symp.*, Philadelphia, USA, Jun. 2018, pp. 583–586.
- [8] B. Beuerle, J. Campion, U. Shah and J. Oberhammer, "A very low loss 220–325 GHz silicon micromachined waveguide technology," *IEEE Trans. THz Sci. Technol.*, vol. 8, no. 2, pp. 248-250, Mar. 2018.
- [9] F. Sammoura, Y.-C. Su, Y. Cai, C.-Y. Chi, B. Elamran, L. Lin, and J.-C. Chiao, "Plastic 95-GHz rectangular waveguides by micro molding technologies," *Sensors and Actuators A: Phys.*, vol. 127, no. 2, pp. 270-275, Mar. 2006.
- [10] V. Fiorese et al., "Evaluation of micro laser sintering metal 3D-printing technology for the development of waveguide passive devices up to 325 GHz," *Proc. IEEE/MTT-S Int. Microw. Symp.*, Los Angeles, USA, Aug. 2020, pp. 1168-1171.
- [11] A. Vosoogh, H. Zirath and Z. S. He, "Novel air-filled waveguide transmission line based on multilayer thin metal plates," *IEEE Trans. THz Sci. Technol.*, vol. 9, no. 3, pp. 282-290, May 2019.
- [12] W. Zixian, G. Shi, Y. Yu, X. Wen, C. Guo, and A. Zhang, "Micro metal additive manufactured low-loss slotted rectangular waveguides operating at 220-500 GHz," *Frontiers Phys.*, vol. 9 pp. 1-7, May, 2021.
- [13] F. Hubert, T. Bader, L. Wahl, A. Hofmann, K. Lomakin, M. Sippel, N. Travitzky, G. Gold, "Additive manufactured waveguide for E-band using ceramic materials," *Appl. Sci.*, vol. 12, no. 1, pp. 1-11, Dec. 2021.
- [14] M. D'Auria et al., "3-D printed metal-pipe rectangular waveguides," *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 5, no. 9, pp. 1339-1349, Sept. 2015.
- [15] B. Zhang, Y.-X. Guo, H. Zirath and Y. P. Zhang, "Investigation on 3-D-printing technologies for millimeter-wave and terahertz applications," *Proc. IEEE*, vol. 105, no. 4, pp. 723-736, April 2017.
- [16] K.V. Caekenberghe, P. Bleys, T. Craeghs, M.J. Pelk and S.V. Bael, "A W-band waveguide fabricated using selective laser melting," *Microw. and Opti. Technol. Lett.*, vol. 54, no. 11, pp. 2572-2575, 2012.
- [17] M. Dressler, T. Studnitzky, M. Stäter, O. Peverini, G. Addamo and H.-U. Nickel, "Preparation and Properties of 3D Screen-Printed RF Components," *IEEE MTT-S Int. Microw. Workshop Ser. on Adv. Mat. Proc. for RF and THz App. (IMWS-AMP)*, Bochum, Germany, 2019, pp. 34-36.
- [18] D. Glynn, T. He, J. Powell, Y. Tian, X. Shang and M. J. Lancaster, "Submillimetre rectangular waveguides based on SU-8 photoresist micromachining technology," *46th Eu. Microw. Conf. (EuMC)*, London, UK, Oct. 2016, pp. 1346-1349.