Low-Loss Sapphire Waveguides for 75–110 GHz Frequency Range

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***Abstract*—Low-loss dielectric waveguides are promising to be used instead of metal ones, but problems in transitions have to be overcome. Simple and effective structure made of monocrystalline sapphire waveguide has been designed. Experimental results at 75–110 GHz indicate good matching with metal waveguide (VSWR ($\leq$1.13) and low insertion loss (0.05–0.35 dB for 47 mm dielectric section).**

***Index Terms*—Metal-dielectric-metal transition, monocrystalline sapphire waveguide.**

I. Introduction

DIELECTRIC materials are intensively used in the technology of millimetre wave and submillimetre wave components, such as waveguides, directional couplers, multistate reflectometers, phase shifters, etc. (see e.g., [1]). Dielectric rod waveguides (DRWs) have lower propagation losses and broader operation frequency band in comparison with the standard single-mode metal waveguides. DRWs have no cut-off frequency for two fundamental modes differing in the X and Y polarization [2], [3]. There are many different types of dielectric waveguides, and devices based on them, developed to date [4]–[6]. The problem with DRWs at short millimetre wavelengths ($f > 75$ GHz), besides employing of low-loss materials, is good matching with metal waveguides. There are several ways of DRW excitation (see e.g., [4], [7]). Typical value of transition loss in this frequency range for one transition is near 0.5 dB [7]. In this letter, we suggest a modified, end-fire excitation scheme using the nonsymmetrical tapering section of the DRW suspended in air without contact with metal. The goal of this letter is to measure the total losses in the dielectric waveguide section in order to study the possibility of designing combined metal–waveguide DRW networks which are of practical interest.

II. Experiment

DRWs were made of monocrystalline sapphire ($\varepsilon\perp = 11.56$, $\varepsilon|| = 9.39$, $\tan\ \delta \sim 10^{-4}$) cut along the optical axis, as shown in Fig. 1, with transitions to standard metal waveguide. The designed transition does not require any horns. This simplifies the construction. The rectangular cross section for the frequency range of 75–110 GHz was chosen according to evaluations in [5] ($k_O b = 1.9$, $a/b = 0.5$). This choice provided relatively small changes of the propagation characteristics of the DRW within the frequency band. The length of the tapering section (6 mm) was chosen so that the angle of tapering was about 9°.

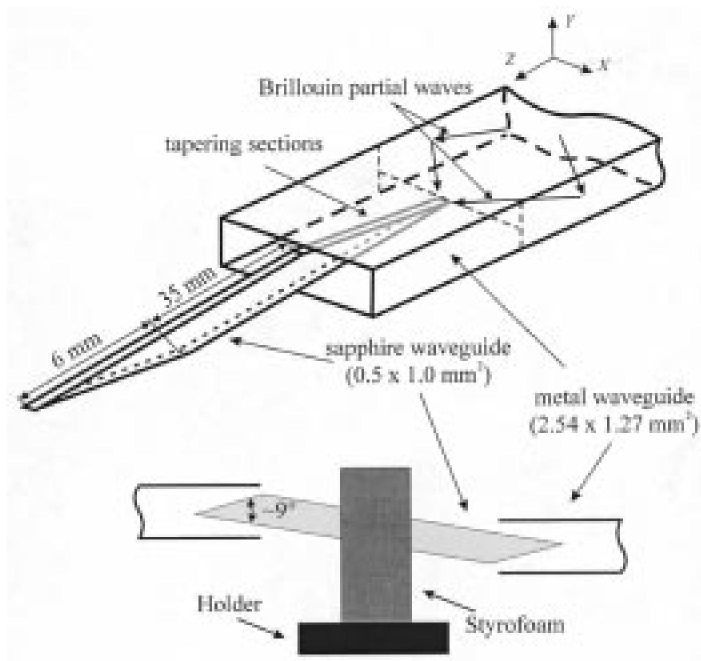

Fig. 1. Transmission setup with the dielectric DRW.

Finite element method (FEM) simulations with HP HFSS software were carried out in order to investigate the preferable plane of the tapering section (E- or H-planes). Simulation results show (Fig. 2) that the tapering in E-plane gives lower insertion losses and smaller reflections. Therefore, the plane of tapering has been chosen in the E-plane.

A nonsymmetrical form of the tapering section (Fig. 1) was chosen because of easier and less expensive fabrication. DRW was supported by a styrofoam holder having only negligible effect on fields. Vector network analyzer HP 8510 (VNA) was used to measure the S-parameter characteristics and was calibrated with respect to the direct connections between input and output metal waveguides of VNA.

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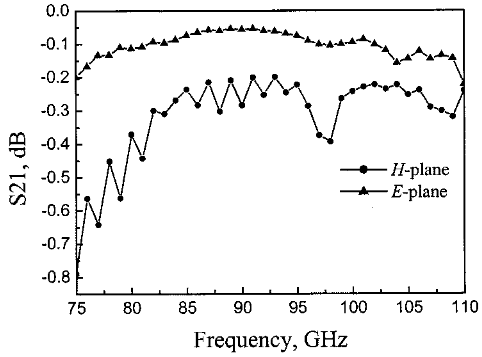

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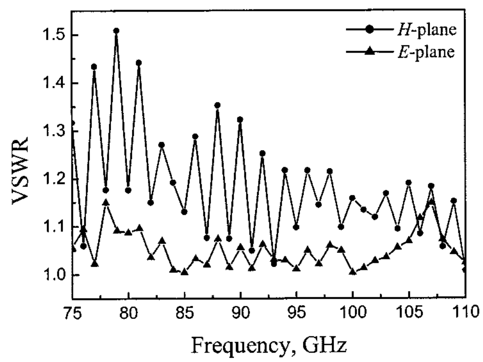

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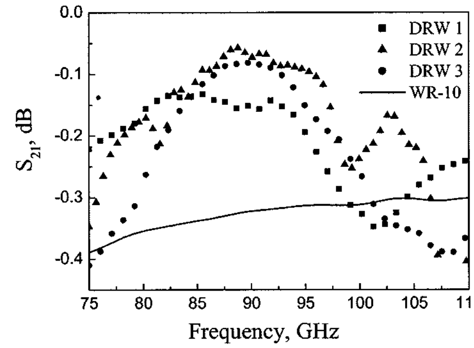
Fig. 2. HFSS simulations of S21 parameter (insertion loss) (a) and VSWR (b) of sapphire waveguide with different tapering planes.



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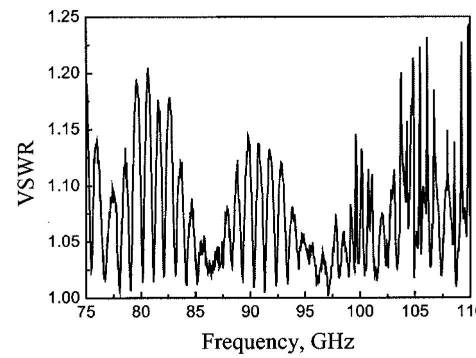

b)

Fig. 3. (a) Measured S21 of three low-loss sapphire waveguides and WR-10 standard waveguide section. (b) VSWR of DRW 1 sample.

III. Results and Discussion

The insertion losses of three 47 mm sapphire waveguides and a WR-10 standard gold-plated waveguide section with approximately the same length (50 mm) are shown in Fig. 3(a). It can be seen that the standard metal waveguide section has an attenuation of 0.3–0.4 dB while the sapphire one has it mainly between 0.1 and 0.3 dB and at some frequencies even near 0.05 dB. Typically, the value of transition loss for one transition from metal waveguide to DRW, or vice versa, varies near to 0.5 dB, depending on the frequency (see, e.g., [7]). In our case, the losses are clearly less than 0.2 dB for one transition. The discrepancy of S21 curves for three sapphire DRWs [Fig. 3(a)] might be because of small discrepancies in the DRW geometry and dimensions due to manufacturing.

Voltage standing wave ratio (VSWR) of sapphire DRW 1 with two tapering sections is shown in Fig. 3(b). The maximum value of VSWR for two transitions is 1.23 (thus, about 1.12 for one transition) that corresponds to a contribution of 0.07 dB to insertion losses due to the wave reflection. According to HFSS, simulations of the main losses at the transition are due to radiation into the environment.

The wavelength in the dielectric waveguide was calculated using Marcatili s method [2] and the result is shown in Fig. 4. It makes it possible to understand the oscillations of the VSWR in Fig. 3(b). The oscillations of the VSWR might be explained

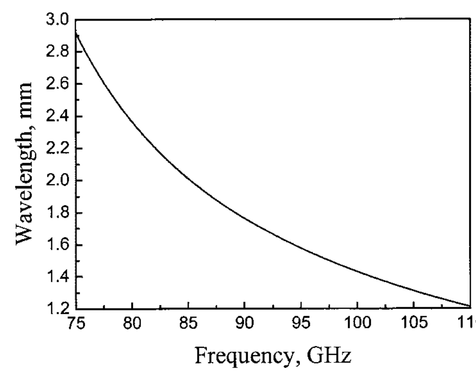

Fig. 4. Wavelength in dielectric waveguide versus frequency calculated by Marcatili's method.

by the interference of two waves reflected from two mode launchers of the DRW. The maxima of the reflection occur at the frequencies of 80.654 and 79.607 GHz, which correspond to wavelengths of 2.310 and 2.398 mm, respectively. The fringe order in this case is $N = \lambda/\Delta\lambda \approx 26$, where λ is the wavelength at higher frequency and $\Delta\lambda$ is the change of the wavelength when the fringe order changes by 1. Thus, the distance between planes of reflections is ~31 mm, which corresponds approximately to the lengths of the sapphire waveguide without the tapering sections. Similarly, for minima of the reflections at other frequencies of 92.368 and 91.334

GHz, which correspond to wavelengths of 1.669 and 1.709 mm, respectively, the length is 36 mm. That is also in good agreement with the geometrical dimension. The discrepancy of the geometrical and calculated lengths can be explained by the fact that Marcatili s method is an approximate one, especially at the low frequency end.

The relatively small value of VSWR might be due to the tapering of DRW in E-plane. In this case, two partial Brillouin waves in the metal waveguide face to the sharp corner of the tapering section of the DRW (Fig. 1). In the opposite case, when the wide wall of metal waveguide is parallel to the wide wall of the DRW, two partial Brillouin waves face the edge of the tapering section, which results in higher reflectivity from such transition.

IV. Conclusion

A simple and effective structure without any horns or additional components has been designed for electromagnetic wave excitation in the "suspended in air" rectangular sapphire DRW with a tapering section non-symmetrical relatively to the optical axis and in the E-plane of the metal waveguide. This structure is easy to manufacture and experimental results of insertion loss and reflection show that the losses in the sapphire waveguide are lower than in the metal one, even below 0.1 dB for 46 mm rod length at about 90 GHz, and VSWR is lower than 1.23. The insertion losses are mainly caused by the transition from metal waveguide to sapphire and vice versa. In spite of small cross-section dimensions of the DRW compared with the metal waveguide, the electromagnetic wave is transmitted to the DRW with very small losses. Thus, it is shown that the materials with relatively high dielectric constant and low-loss tangent, like sapphire, Si, GaAs, etc., could be successfully employed as the DRW and can have extremely low insertion losses at the frequencies above 75 GHz.

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