Flexible Low-Loss Dielectric Waveguides for THz Frequencies with Transitions to Metal Waveguides

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***Abstract*— A flexible low-loss dielectric waveguide system for sub-millimetre wave frequencies up to 600 GHz is presented, with measured attenuation values shown at 300 GHz. Mode transformers for an accurate and reproducible transition to metal waveguides have been investigated and improved.**

I. INTRODUCTION

In addition to waveguiding structures formed by electrically conducting materials, electromagnetic waves can also be guided by electically insulating materials.

Using this effect, rectangular waveguides made from dielectric materials have proven to be a very capable alternative to conventional metal waveguides and quasi-optical waveguide assemblies at millimeter wave frequencies for more than 30 years [1]-[4],[10] because of their low attenuation, bending flexibility and rather low cost of manufacture.

As the THz-frequency range has become of interest for spectroscopic applications, the demand for flexible, low-attenuation waveguides at sub-millimetre wave frequencies is increasing. Dielectric waveguides made from high-density polyethylene (HD-PE) are highly suitable for this purpose and can also be used for mobile applications because of their low specific weight of 0.935 - 0.965 g/cm^3 [5].

They have now been fabricated and evaluated for frequencies around 300 GHz, 450 GHz and 600 GHz.

II. DESIGN AND FABRICATION

Though circular dielectric waveguides are simpler to process, our dielectric waveguides were designed with a rectangular cross-section. This entails the following advantages [6]:

- The polarisation of guided waves is well defined;
- Transitions to rectangular waveguides are quite simple.

For best performance, the dielectric waveguide was designed to fit accurately into the related metal waveguide.

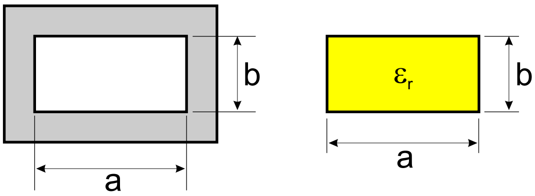

Fig. 1. Cross-sections of the metal waveguide (left) and the dielectric waveguide (right)

At 300 GHz, the dimensions of a standard WR 3 rectangular waveguide are a = 0.864 mm and b = 0.432 mm. At 450 GHz and 600 GHz, there are no standards available for rectangular waveguides any more. The dimensions were chosen to be a = 0.560 mm and b = 0.280 mm (f_{cutoff} = 267.7 GHz, frequency range 320 GHz - 510 GHz) and a = 0.4 mm and b = 0.2 mm (f_{cutoff} = 374.7 GHz, frequency range 450 GHz - 710 GHz).

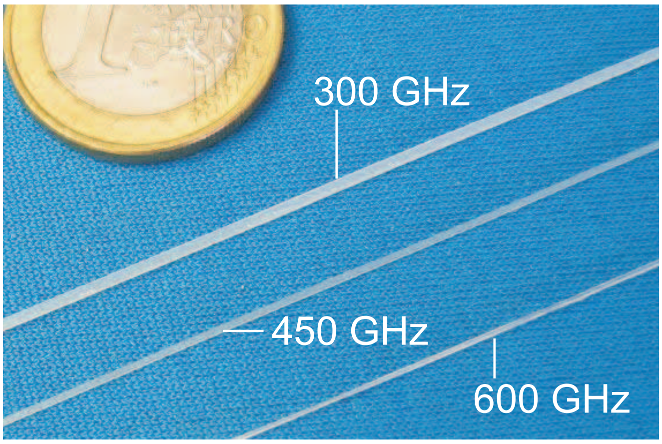

Fig. 2. Dielectric rectangular waveguides for 300 GHz, 450 GHz and 600 GHz

The dielectric waveguides were made from low-loss, high-density polyethylene (HD-PE).

At 300 GHz, this material is specified to have a dielectric constant ε_r of 2.32 and a loss tangent (tan δ) of $3.9 \cdot 10^{-4}$ [7]. The HD-PE dielectric waveguides were extruded, rolled to the desired thickness and finally cut to the correct width.

Inevitably, strong material tensions are induced by this treatment. To prevent the waveguides from coiling up, waveguide pieces with a length of 2 m were set under tension for at least 6 weeks. The tension was checked continuously. Its minimum value was set to 25 N in the centre of the waveguide. Afterwards, the coiling virtually was eliminated.

III. MEASUREMENT OF PERFORMANCE

The attenuation of a dielectric waveguide at 300 GHz has been analysed with a backward wave oscillator (BWO) as a radiation source and a spectrum analyser with an external mixer as power detector.

In order to eliminate the attenuation influence of the waveguide transitions described in the following section, two dielectric waveguides with different known lengths l_1 and l_2 were used (see figure 3).

After measuring the attenuation a_m of the entire waveguide system consisting of the dielectric waveguide with the length

l_1 or l_2 and two transitions to metal waveguide, the attenuation of the dielectric waveguide can be calculated.

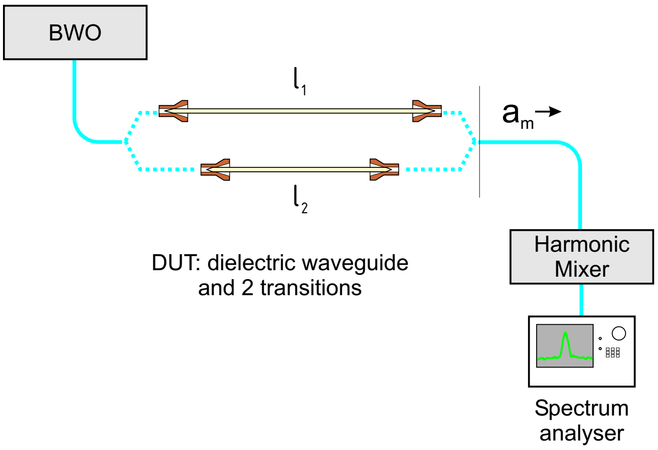

Fig. 3. 300 GHz dielectric waveguide attenuation measurement setup

The measurement results are presented in Figure 4. For comparison, the theoretical attenuation of a rectangular waveguide made from coin silver is also shown.
The dielectric waveguide has a significantly lower attenuation compared to the theoretical metal waveguide values.

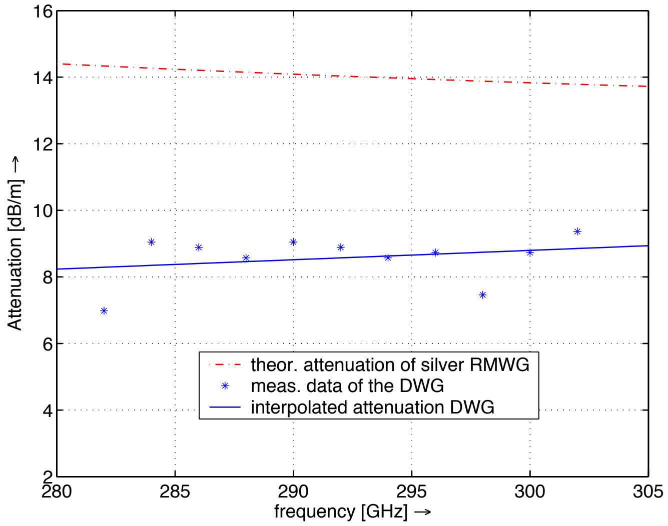

Fig. 4. Comparison between the measured and interpolated attenuation of the dielectric waveguide (DWG) and the calculated attenuation of a WR 3 coin silver rectangular metal waveguide (RMWG)

Practical experience shows that the difference is even bigger according to somewhat idealised theoretical values in data sheets.
As an empiric rule of thumb, the attenuation values of the dielectric waveguides (in dB/m) roughly double at double frequency, provided that the dimensions of the dielectric waveguides match the inside dimensions of the mono-mode metal waveguides suiting to the respective frequencies.
Consequently, an attenuation of 14 dB/m can be extrapolated for a dielectric waveguide at 450 GHz, respectively 19 dB/m at 600 GHz (figure 5).

IV. WAVEGUIDE TRANSITIONS

For using dielectric waveguides in metal waveguide based setups, specially designed transitions, so called mode transformers (MT), are necessary.
The transition consists of two regions, that can be identified as follows [8]:

- The "taper", a transition from air-filled to dielectric waveguide, as the dielectric waveguide is inserted into the metal waveguide.
- The "horn", the mechanism whereby the wave is launched from the metal-boundary dielectric waveguide to the air-boundary dielectric fibre.

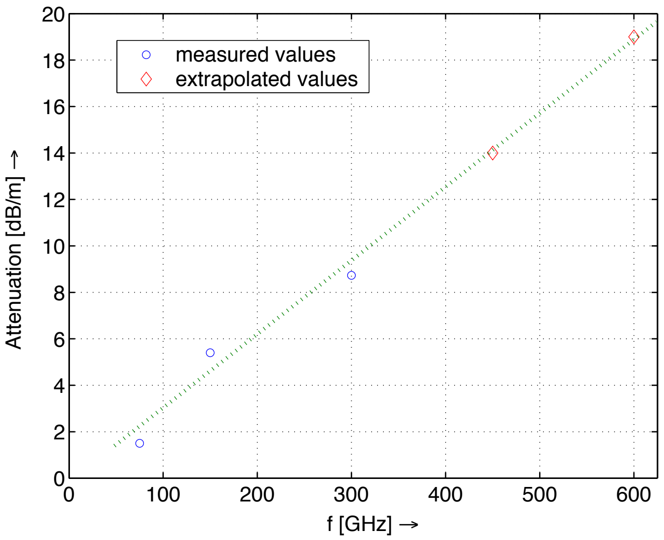

Fig. 5. Measured and extrapolated attenuation values of the dielectric waveguide at different frequencies

Extensive simulative research was done by Fluhrer [9]; [10] to determine the optimal aperture opening angle of 38° (circular aperture) for maximum power transmission.
To achieve a decrease of the electro-magnetic field down to -30 dB or less related to the field maximum at the edge of the horn, an aperture diameter of 10.0 mm was found necessary at 150 GHz.
This can be scaled down to a diameter of 5.0 mm at 300 GHz (3.3 mm at 450 GHz and 2.5 mm at 600 GHz) .

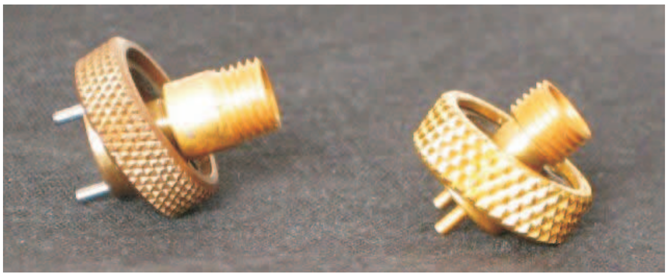

Fig. 6. Waveguide transitions with fixed (right) and demountable (left) horn

First MTs were realized for 300 GHz (Figure 6, right transition). As the dielectric waveguides are very flexible because of their tiny cross-sections, their insertion into the MT by hand proved to be very difficult .

Therefore, a novel concept for the MT with a demountable horn was developed and fabricated (Figure 7).

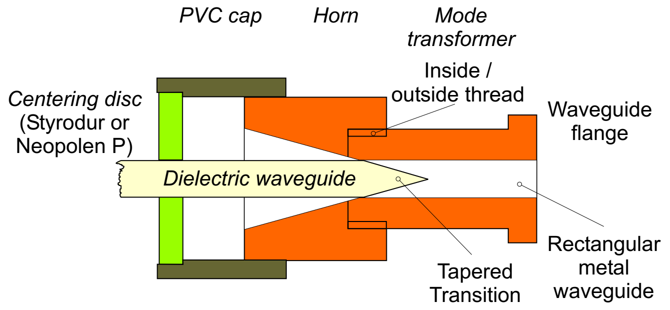

Fig. 7. Schematic diagram of a MT with demountable horn and centering disc; The dielectric waveguide is tapered to reduce reflections

After demounting of the horn, the dielectric waveguide can now be controlled and reproducibly inserted, without being damaged.

For measuring the performance of the new design, scaled models for the WR 12 frequency range were manufactured and tested by the following setup shown in Figure 8.

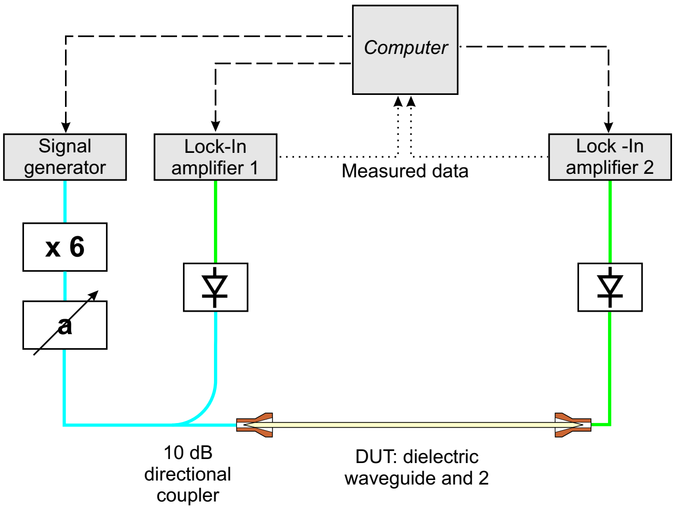

Fig. 8. Computerised transmission measurement setup for automatic test

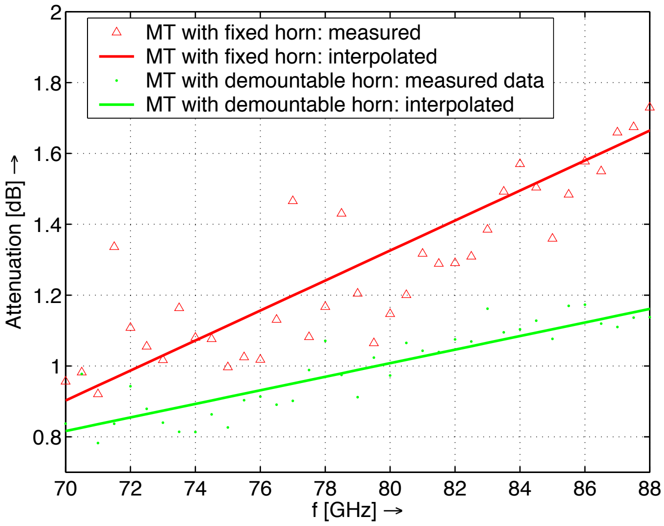

Fig. 9. Comparison between demountable and fixed MTs, scaled models at 75 GHz

A piece of dielectric waveguide with a fixed length of 0.38 m was combined with a pair of demountable and a pair of fixed horn MTs.

The total attenuation of both combinations versus frequency was investigated by the setup above and is presented in figure 9.

The mode transformer with the demountable horn shows lower attenuation over the entire frequency range.

The interpolated curve of the fixed mode transformer shows a higher gradient. Thus, the difference of the measured attenuation values between both versions of the mode transformer at one frequency increases towards higher frequencies.

In addition, a smaller deviation of the measured values from the interpolated values can be achieved by using MTs with demountable horns.

These phenomena can be explained by the insertion of the dielectric waveguide with higher precision.

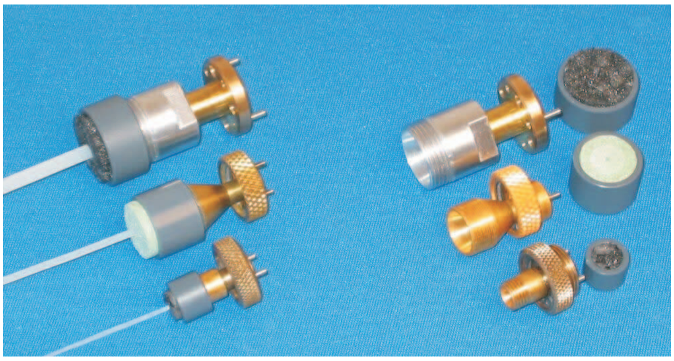

Fig. 10. Waveguide transitions of different frequency ranges (from top to bottom: WR 12; WR 6; WR 3) with accessories kit for centering the dielectric waveguide; On the left side in the picture, the accordant waveguide transitions are shown ready for use with an inserted waveguide

V. CONCLUSION

A flexible waveguide system made of high-density polyethylene has been designed and for the first time fabricated for frequencies at 300 GHz, 450 GHz and 600 GHz. Measurements at 300 GHz successfully verified the more than 4 dB/m lower attenuation compared with conventional metal waveguides.

A novel concept for mode transformers allows for controlled and reproducible insertion of THz dielectric waveguides.

The developed flexible waveguide system is well suited for multiple applications like THz field probing, space-based communications, as well as chemical and biological sensing.

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