International Journal of Scientific Research in Modern Science and Technology
ISSN: 2583 -7605 (Online)
© IJSRMST \ Vol. 2 \ Issue 6 \ June 2023
Available online at: www.ijsrmst.com
DOI: https://doi.org/10.59828/ijsrmst.v2i6.94

A Novel Low-Loss Overmoded Waveguide System for mm-Wave Cosmology

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ABSTRACT

Millimeter-wave signals need to be carried over distances of ~1 meter or more with low loss for applications in precision cosmology such as beam pattern measurements of antennas. We present a novel, particularly simple approach to convert from standard rectangular waveguide to an overmoded circular waveguide and back again. We give a design for a transition from rectangular W-band (75-110 GHz) waveguide to overmoded circular waveguide and for long circular waveguides made of copper tubes. The measured loss of the transitions is below 0.25 dB and the loss in the circular waveguide is ~ 0.7 dB over a 3 m length, including circular waveguide joints at each end. This result is consistent with calculations.

Index Terms: Wave signals, novel, cosmology, overmoded circular waveguide.

1. INTRODUCTION

Precision astrophysical instruments require careful calibration of antenna beams. In particular, the field of CMB polarization requires exquisite precision in antenna beam-mapping for systematic effect control [1]. Several methods have been used in engineering, but most suffer from a variety of drawbacks. Long runs of rectangular waveguide typically have losses of several dB/m. Typical coaxial lines offer flexibility but are even lossier. Large diameter coaxial lines are flexible and offer reduced loss but are expensive. Beam waveguides, in which gaussian beams are transported between refocussing lenses or mirrors are large in diameter and require careful alignment. We describe a simple novel technique to propagate a signal in the W-band (75 - 110 GHz) over ~20m or more without appreciable loss. The technique is easy to implement, does not require elaborate fabrication, and can be implemented in any millimeter-wave waveguide. It involves propagating the signal through a small section of standard waveguide and then transitioning to a larger circular waveguide (i.e. overmoding) for ~20m. We then transition back to WR-10 and measure the transmisson through the entire system. Although overmoded waveguides have been used for this purpose before, our implementation is particularly simple and inexpensive. This overmoding technique depends on low-loss transitions. In order to be low-loss, these transitions had to be smooth and gradual. We designed a 5 cm long transition from WR-10 to a 7.6 mm (0.30 ") inner diameter circular waveguide. The reason for this choice was that copper tubes of this diameter are readily available. Earlier work on overmoding (see, e.g. [2]) has emphasised the development of theoretical models and optimization of instrumental

IJSRMST | Received: 05 June 2023 | Accepted: 10 May 2023 | Published: 14 June 2023

arrangement/setup to reduce losses, and maximize mode transport through the overmoding mechanism, especially for large amounts of input power. Our approach, on the other hand, is straightforward: other than a high-precision transition from W-band to circular waveguide we use standard and equipment (long copper tubes) to probe the efficacy of the general overmoding technique for low power applications($< 100mW$).

2. THEORY - LOSS IN A WAVEGUIDE AT ROOM TEMPERATURE

We now calculate the loss in a waveguide that occurs due to the resistive element of the waveguide material. We do this calculation for two waveguide systems: 1) Rectangular W-band waveguide made of silver 2) Circular 0.3” Waveguide made of copper A naive first assesment would assume a lower loss in (1) above, because silver is a better conductor than copper. We show below that resistive losses depend on dimensions as well as material conductivity. For a section of waveguide of length z, teh ratio of the amount of power in the TE10 mode, which carries almost all the transmitted power, to the input power P0 is given by

$$\frac{\mathrm{P}_{10}}{\mathrm{P}_0} = e^{2\alpha}z \qquad (1)$$

where α is the “attenuation constant” and is measured in Np/m. Let us calculate the attenuation constants for the two cases, followed by an estimate of the loss through a waveguide length of 60’ in each case. This is the maximum length for which we measured the loss through a circular copper waveguide as explained in later sections.

A. **Rectangular W-band waveguide**

For a rectangular waveguide, the attenuation constant is given by [3]:

$$\alpha = \left(\frac{R_m}{Z_0}\right)\frac{1}{\alpha b\beta_{10}k_0}(2bk_{e10}^2 + ak_0^2) \qquad (2)$$

R_m = Real part of surface impedence = of the waveguide

Z_0= Impedance of free space

a, b= Dimension of waveguide

k_0= Wave number in free space

k_{e10}= Wave number corresponding to cut off Frequency

λ_e, f_e = Cutoff wavelength and

= frequency respectively

β = Propagation factor

β_{10}= Propagation factor for TE_{10} mode (3)

For the W-band, the parameters are as follows:

f ≡ centre frequency = 93 GHz

, f_c= 60 GHz

a = 0.10≡ 0.254 cm

b = 0.05≡ 0.127 cm

$k_0 = \frac{2\pi}{c} f$ = $1947.79m^{-1}$

$\beta_{10} = \frac{2\pi}{c}\sqrt{f^2} - f_e^2$ = $1488.20m^{-1}$

$$k_{e10} = = \frac{2\pi}{c} f_e = 1256.64m^{-1}$$

$$R_m = \frac{1}{\sigma\delta} \equiv \sqrt{\frac{\pi f \mu}{\sigma}} = 0.078 \text{ for silver}$$

$$Z_0 = 377\Omega \tag{4}$$

With these values, the attenuation constant, α is calculated to be

$$\alpha = 0.303\text{Np/m} \tag{5}$$

The ratio of transmitted power for a 60’-long waveguide section is given by

$$\frac{\mathrm{P}_{10}}{\mathrm{P}_0} = e^{-2\times 0.303\times 18.288} = 1.54 \times 10^{-5} \equiv -48dB \tag{6}$$

B. Circular Waveguide: 0.3”

The attenuation constant for a circular waveguide is given by [3]

$$\alpha = \left(\frac{R_m}{Z_0}\right)\frac{1}{\alpha}\left(\frac{1.841^2}{k_0^2 a^2}\right)^{-\frac{1}{2}}\left(\frac{1.841^2}{k_0^2 a^2} + 0.4185\right) \tag{7}$$

a = Diameter of waveguide = 0.3 ″ = 0.00762m

R_m = 0.0795 for copper (8)

With these values, the attenuation constant, α is found to be

$$\alpha = 0.0121\text{Np/m} \tag{9}$$

for a 0.3” circular copper waveguide. The ratio of transmitted power for a 60’-long waveguide section is given by

$$\frac{\mathrm{P}_{10}}{\mathrm{P}_0} = e^{-2\times 0.0121\times 18.288} = 0.642 \equiv -1.92\text{dB} \tag{10}$$

3. EXPERIMENTAL SETUP

An HP83751A 2-20GHz synthesized sweeper followed by an active quadrupler and passive doubler is used to sweep from 75-110 GHz. The sweeper is followed by a WR-10 waveguide attenuator. A rectangular to circular transition of length 5 cm makes the transition to 7.6 mm diameter overmoded circular waveguide. The transition is attached to copper tubing with the same inner circular diameter. The copper tubing comes in 3 m (10 ’) segments and 0 to 6 segments of tubing was used in a variety of experiments. The circular waveguide joints include a cylindrical step on the one face that fits into a mating groove in the other face. The groove is designed so that contact occurs at the waveguide wall. After the copper tubing another circular to rectangular transition converts back to WR-10 waveguide, followed by a waveguide detector diode. The detector signal is measured by an HP8757C Scalar Network Analyzer.

4. MEASUREMENTS

A. Calibration

The circular apertures of the two rectangular to circular transitions were attached together to measure the loss through them and to form a calibration for the subsequent tests of the circular waveguide. The combined loss is less ~0.5 dB, or less than ~ 0.25 dB per transition.

B. Raw Data

Measurements of S_{21} were made of the 3 m circular waveguides (pipes), with up to 6 pipes assembled in series. Raw data is shown in fig.(3). These measurements have not been corrected for the baseline calibration measurement. It is clear that the loss increases monotonically with the length of the copper tube at all frequencies. Standing waves in the tube make it difficult to make accurate comparisons between lengths, so the smoothed data is used to estimate the loss/length.

C. Smoothed data

The smoothed data sets are made using the smoothing function on the network analyzer. This special function creates 5% smoothing and attenuates the resonances. On this graph the similarities between different lengths are even more obvious.

The overall structure of each graph appears to be the same, except shifted down due to the increased loss in the additional tubing. The baseline test varies the most, but even that is reasonably similar everywhere except the high frequencies (> 105 GHz).

D. Calculation of loss

The power loss per 3 m length of tubing was calculated by averaging the differences in power for each additional 3 m of copper tubing. This approach removes the baseline calibration. The standard deviation was then found for each average and was graphed as well (in black). The average loss was -0.82 ± 0.31 dB per 3 m length, or -0.27 dB/m. This is slightly more than the expected -0.11 dB/m; the extra loss is undoubtedly associated with the circular waveguide flanges.

E. Standing waves in the copper tube

To further explore the standing waves, data were taken over a small range (90–90.4 GHz). This allows the resonances to be easily counted and compared with calculations. If the number of cycles is compared, for each peak in the 10’ segment there are 2 peaks in the 20’, 3 peaks in the 30’, etc. Calculations also show that the number of resonances in each length for .4 GHz is what would be expected for standing waves in that length.

For any given length ℓ, the difference in frequency between two crests of the resonances is given by $\Delta f = \frac{c}{\lambda} \equiv \frac{c}{2l}$. Δf for 3.05,6.09,9.14,12.19,15.24 and 18.29m(10,20,30,40,50 and 60 feet) is 0.0492, 0.0246, 0.0164, 0.0123, 0.0098 and 0.0082 GHz respectively ⇒ 8, 16, 24, 32, 40 and 48 resonances in 0.4 GHz, which is the number we find in the measurement. This proves conclusively that the oscillations seen in the raw data are indeed standing waves. The amplitude of the waves is very stable, even when the pipes are flexed.

5. CONCLUSIONS

We have demonstrated a practical way to reduce the loss in a long waveguide by increasing its diameter, without the need for sophisticated equipment or analysis techniques. Over a length of 18 meters, the total waveguide loss is ~ 5 dB. This is a significant improvement over the predicted 50 dB loss in Wband rectangular waveguide.

ACKNOWLEDGEMENTS

Siddharth Savyasachi Malu was supported by the GrantIn-Aid-of-Research sponsored by the Academy of Sciences and administered by Sigma-Xi; grant no. 20063131556544060.

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FUGURES:

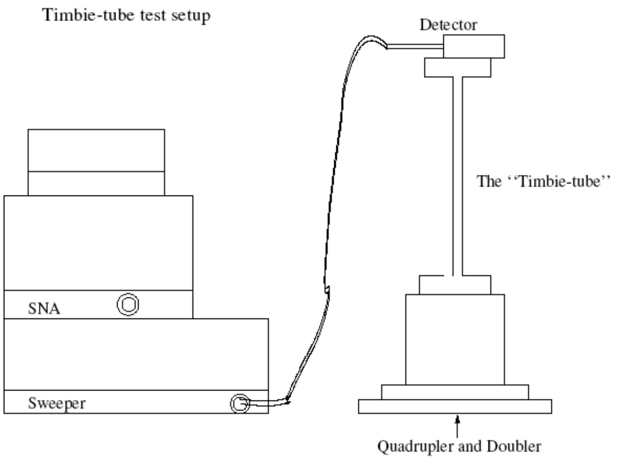

Fig. 1: The set-up of the loss test for overmoded signal

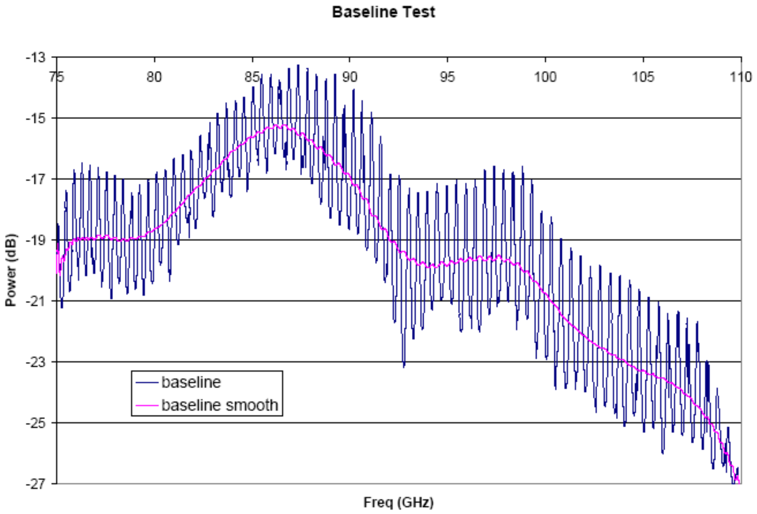

Fig. 2: Transmission through pair of rectangular to circular transitions. This measurement is the baseline that is to be removed from subsequent tests of the various lengths of circular waveguide. The ripples that are caused by standing waves in the transitions are removed by using the smooth function on the SNA.

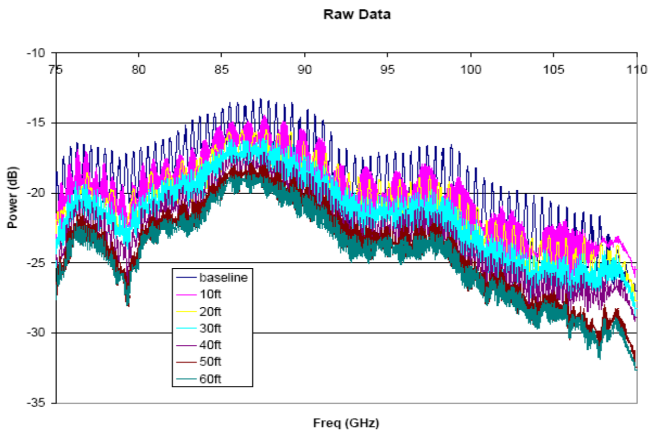

Fig. 3: Raw data for various lengths of the copper tube. Notice that the amplitude of the oscillatory features and the spacing between resonances decreases as the length of the tube is increased.

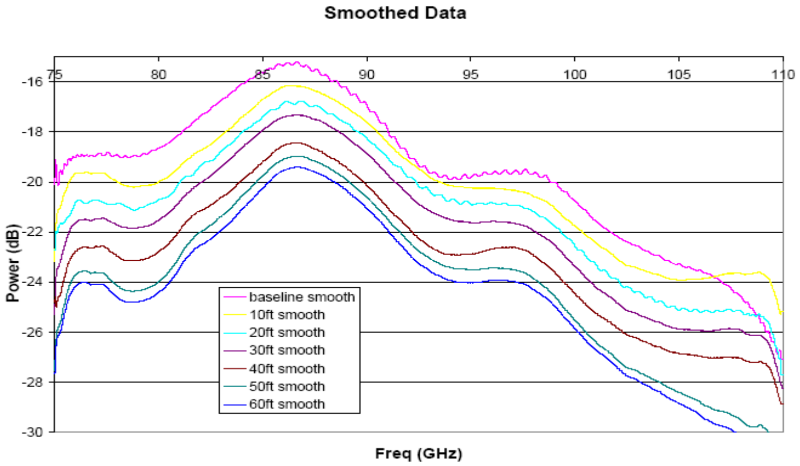

Fig. 4: Data obtained by using the smooth function on the SNA. Notice that the resonances are attenuated, but the power level for each length remains the same. This allows an estimation of loss per unit length.

Cite this Article:

Siddharth Savyasachi Malu and Peter T. Timbie, "A Novel Low-Loss Overmoded Waveguide System for mm-Wave Cosmology ", *International Journal of Scientific Research in Modern Science and Technology (IJSRMST), ISSN: 2583-7605 (Online), Volume 2, Issue 6, pp. 01 - 06, June 2023.*

Journal URL: https://ijsrmst.com/