The LLWG: A Low-loss, Low-cost, Small-diameter THz Waveguide for MAS-DNP in NB Magnets

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Introduction

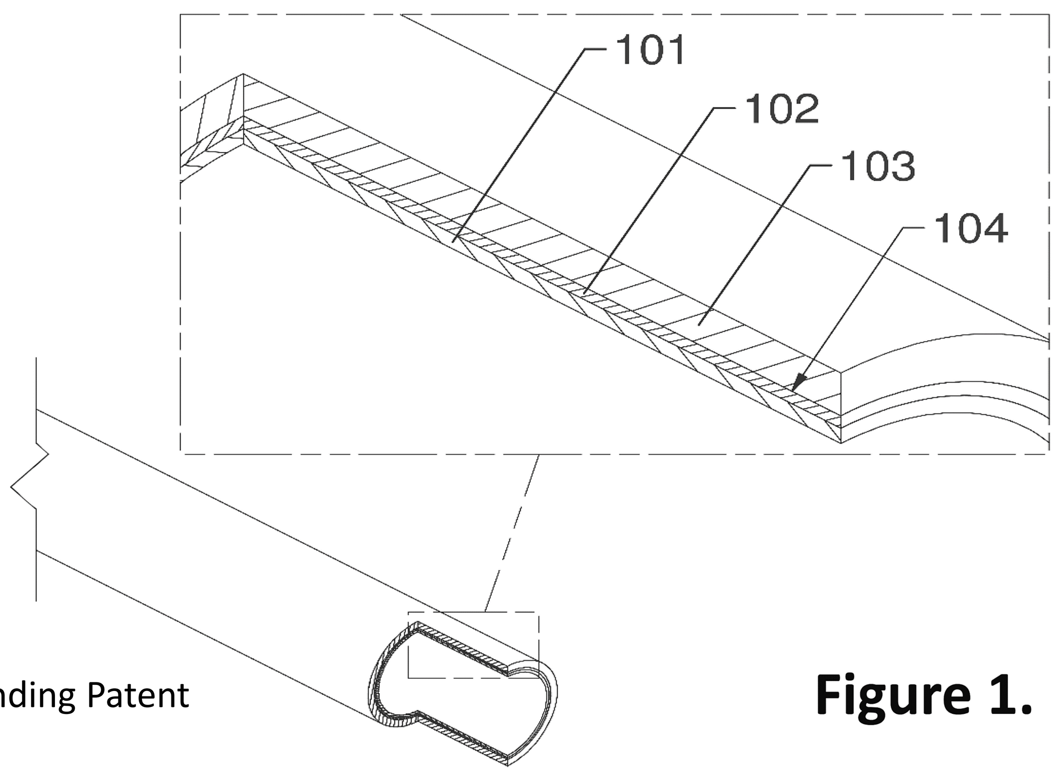
A novel waveguide (WG) for the 70-1500 GHz range has been developed that achieves loss more than 100X below that of fundamental-mode waveguides at 400 GHz, comparable to that of the very expensive corrugated waveguides of similar size, but much more manufacturable. The Laminate-Lined WaveGuide (LLWG) can easily be made with outside diameter (OD) below 5 mm. Manufacturing cost is expected to be about one tenth that of corrugated WGs, especially above 300 GHz and for smaller diameters.

Motivation

- **Reduce the cost of MAS-DNP – by eliminating the need for a specialized WB magnet, gyrotron, and corrugated WGs.**
- **Enable MAS-DNP in NB magnets – requires a smaller WG.**
- **Enable high-field DNP with solid-state sources – requires operating at Ultra Low Temperature (ULT).**

Description

The LLWG comprises a single-clad flexible microwave laminate rolled into a cylinder with its copper surface outward and its dielectric surface facing inward. The rolled laminate is supported inside a metal tube. Figure. 1 illustrates a cross-section view of the LLWG. In it one sees the laminate dielectric layer 101, the laminate copper layer 102, and the support tube 103. The rolled single-clad laminate strip is a snug fit inside the support tube, with its two longitudinal sides abutting along edge 104.



Pending Patent

Figure 1.

Experiments/Simulations/Results

Like the corrugated WG, the novel LLWG supports quasi-Gaussian HE_{11} mode for efficient coupling, and it suppresses most parasitic modes.

For d_i over range of 3-9 λ (where d_i is the inside diameter of the waveguide) loss scales approximately with $1/d_i^2$. Losses increase more rapidly at diameters below 3 λ, and they decrease less rapidly at diameters above 9 λ.

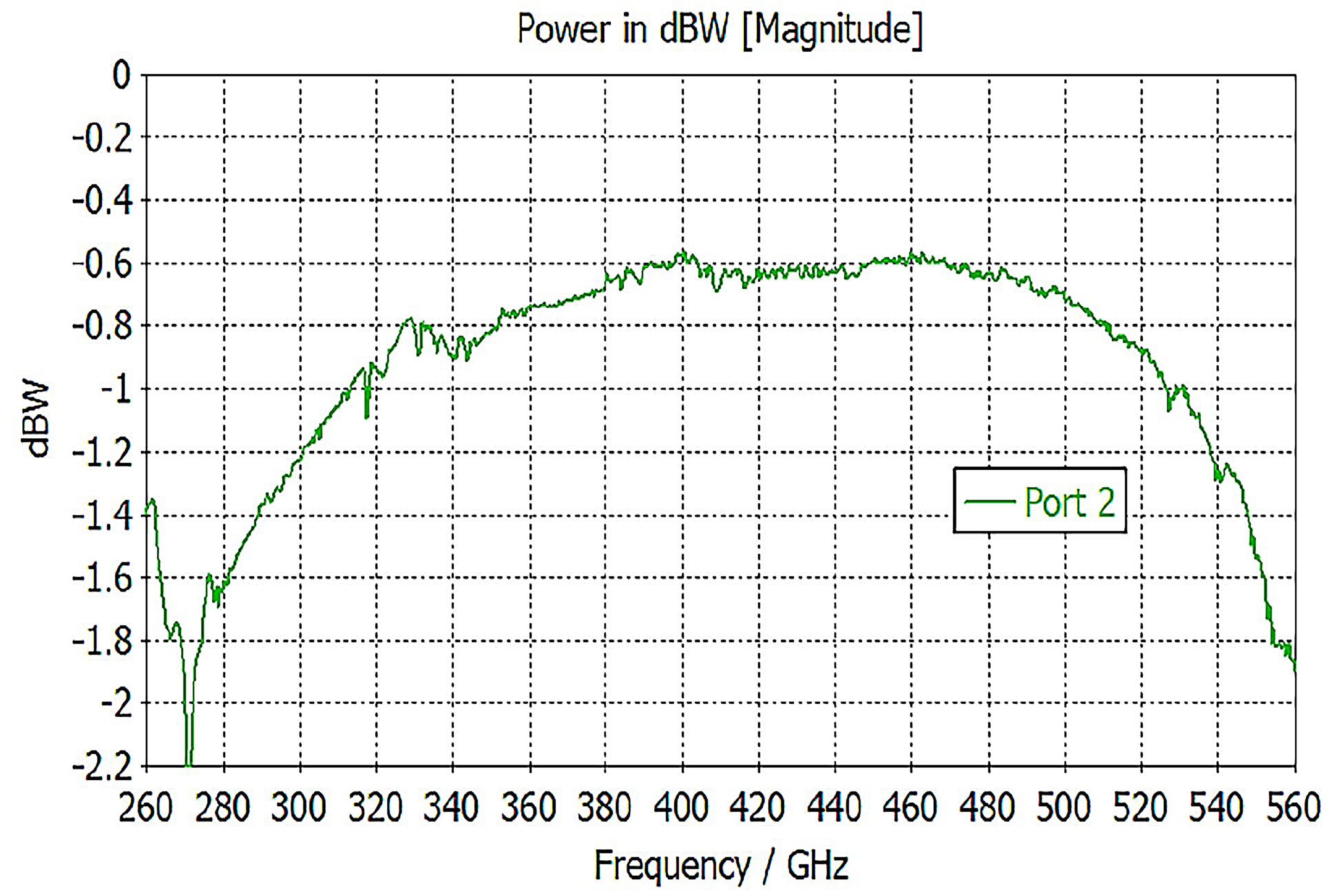
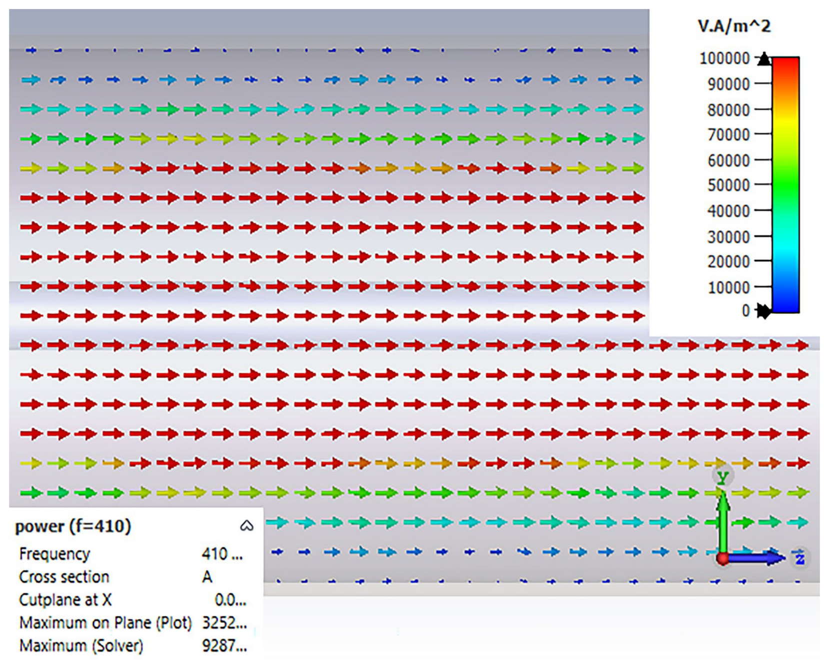


Figure 2 shows simulated power loss for a waveguide of 4.8-mm inside diameter (ID) made using PTFE laminate with dielectric thickness 0.127 mm, corresponding to $\lambda_d/4$ at 410 GHz for ε=2.08. The loss tangent was 0.001 (for PTFE at 400 GHz), and the copper conductivity was set at 3E7 S/m to account for surface roughness. Here, the waveguide length was 500 mm, and it was excited with 1 W of HE_{11} (0.95*TE_{11} plus 0.31*TM_{11}) with quasi-Gaussian profile.

Small defects were included in the numerical model as proxies for typical manufacturing defects. The left scale shows power accepted at the output port (sum of all modes, mostly TE_{11} and TM_{11}). The loss in dB/m would be about twice the numbers shown on the vertical scale, as input and output coupling losses were each only ~2%. The mid-range loss is seen to be ~1.2 dB/m.



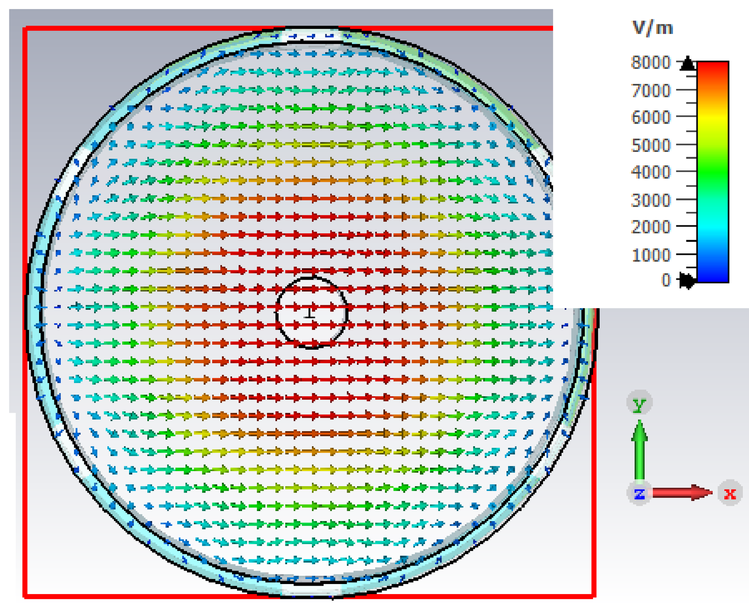


Figure 3 (above left) shows the Poynting vector (power flow) mid-way for the same LLWG. Figure 4 (right) shows the E vector field on the z=400 mm plane in the same 500-mm-long LLWG. Note the desired quasi-Gaussian radial intensity profile and linear field mode.

Tapered Laminate-lined Transitions:

The corrugated WG from the gyrotron to the probe usually has ID in the 15-19 mm range and OD in the 20-26 mm range. That large size reduces losses and manufacturing cost. However, that doesn't fit inside the probe (especially if NB!) so the beam diameter must be reduced. Doing that without causing unwanted mode conversions and losses has required corrugated tapered transitions, which are even more costly than straight corrugated WGs. A laminate lining in place of corrugations here again works beautifully – generally better than corrugations, as it is very challenging to produce corrugated tapered transitions with the precision needed.

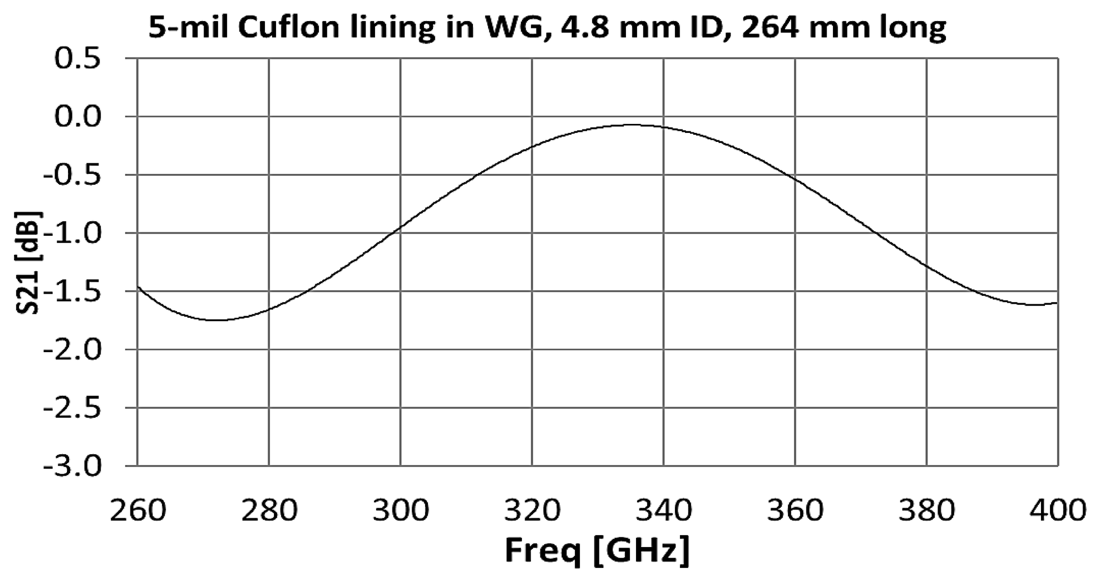


Figure 5. Fourth-order fit to experimental loss measurements for a LLWG of ~6-mm OD, lined with 5-mil Cuflon.

Discussion and Ongoing Work

We are working toward enabling high-field MAS-DNP in NB magnets using solid-state sources. While such sources are currently more than an order of magnitude shy of the power often used in high-field DNP, there appears to be opportunity to reduce the microwave power needed by up to two orders of magnitude from the combination of 1) a high-mode THz cavity compatible with MAS, and 2) operation below 35 K.

The novel Laminate-Lined Waveguide (LLWG) is being integrated into a NB ULT MAS probe for DNP that includes a high-mode THz cavity and is expected to permit routine low-cost operation below 15 K. We anticipate being to the point of presenting results from this probe a year from now. The probe will combine a number of innovations, including the LLWG, that will make UHF ULT MAS-DNP in NB magnets not only possible, but also affordable. Stay tuned!

Conclusion

An improved dielectric-lined cylindrical waveguide and method of fabricating such has been developed that is particularly useful in the 0.07 to 3 terahertz frequency range. It has substantial cost and size advantages relative to corrugated waveguides, performance advantages relative to prior dielectric-lined waveguides, and coupling, bandwidth, and cost advantages relative to micro-structured-fiber waveguides.

Acknowledgements

1. **Doty FD, Doty GN, Staab JP, Sizyuk Y, and Ellis PD, "New Insights from Broadband Simulations into Small Overmoded Smooth and Corrugated Terahertz Waveguides and Transitions for NMR-DNP," J. Magn. Reson. Open, 2021.**
2. **Doty FD, "A Novel Waveguide to Enable MAS-DNP-NMR in Standard-bore High-field Magnets", 1 R43 GM139468-02, 2023.**
3. **Doty FD, Rolled-Laminate Waveguide, US provisional pending patent, 2/2022.**