Research Highlight #144

Hyperbolic-cosine waveguide tapers and oversize rectangular waveguide for reduced broadband insertion loss in W-band electron paramagnetic resonance spectroscopy

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Introduction: A sample to be investigated by high-frequency EPR spectroscopy is generally placed in a resonator supported inside a cryogenic magnet. A typical distance between the resonator and the microwave bridge is 1 m. Thus, in conventional rectangular waveguide at 94 GHz, more than half of the power incident on the transmission line is lost and the signal-to-noise ratio is reduced. Known methods to reduce insertion loss include use of corrugated cylindrical waveguide and use of so-called “tall waveguide.” These waveguide types can be called oversize since they can support higher order propagating modes in addition to the main mode. Whatever the method used to reduce insertion loss relative to standard rectangular waveguide, it is necessary to employ a mode-conversion device at both ends of the low-loss waveguide segment. A problem in the use of oversize waveguide is that any mode converter or any mechanical imperfection in the oversize section will excite higher order modes that can propagate in the oversize waveguide. These modes resonate at particular frequencies determined by the length of the oversize waveguide and these resonances can be seen in the transmission and reflection coefficients of the main mode through an oversize section. Such narrow-band perturbations in the signal cannot be tolerated in many types of EPR experiments, including a subject of current interest: frequency-swept EPR at W-band. We have developed a novel design [1] that uses the commonly available rectangular WR28 as the oversize waveguide and the rectangular TE_{10} mode for carrying the signal. The design has a straight section of WR28 and two tapers shaped according to a hyperbolic cosine (HC) function that provide a transition to the conventional rectangular WR10 waveguide.

Figure 1: Photographs of the HC taper pair. (a) End detail showing, from left to right, UG-599 WR28 flange, custom high-precision WR28 flange, ALMA WR10 flat flange. (b) Assembled taper pair with 132 mm WR28 oversize waveguide section.

Methods: From mode coupling theory [2], it can be concluded that a taper with zero flare at each end and a maximum in between (an “S” shape) is superior to other shapes because it permits a broadband spatial interference to minimize the coupling to higher order modes. Calculations indicate that the optimum position of maximum flare is near the small end of the taper. Performance comparisons between the single-pass theory and Ansoft HFSS simulations revealed only minor differences. The optimum HC taper shape determined by mode coupling theory was converted to initial graphics exchange specification (IGES) files, which were used by A. J. Tuck (Brookfield, CT) for computer-controlled fabrication and electroforming, Fig. 1. It was subsequently found that alignment imperfections in the standard high precision UG-599 WR28 flanges produced resonances of higher order modes that exceeded those produced by the HC tapers. Positional tolerance for the alignment pins of these flanges is $\pm 50\ \mu$m. Consequently, a special high-precision flange was designed and fabricated by us, Fig. 1. The flange surrounds the UG-599 flange (with no pins) on five sides. Twelve silver-tipped set screws permit alignment adjustment in two dimensions. Once alignment is made, four other screws form a permanent fixture once tightened. The alignment between interior waveguide faces was estimated to be about $5\ \mu$m.

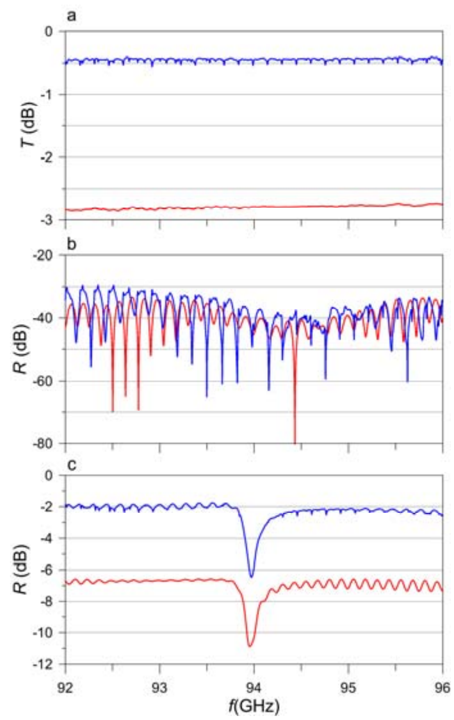

Figure 2: Transmission and reflection coefficient comparison between 96 mm HC tapers with 711 mm section of WR28 (blue) and 902 mm section of WR10 (red). (a) T. (b) R. (c) R with slightly detuned LGR with 38 mm section of WR10.

Results: Measurements for the 1 m section of WR28 are shown in Fig. 2 and compared to a similar length of WR10. The overall insertion loss of the oversize section is about 0.5 dB, nearly six times smaller than the WR10. Sinusoidal fluctuations in *T* caused by misalignment of the WR10 flanges is apparent in the WR10 curve. Similar fluctuations occur in the oversize section, but there are also sharp dips caused by higher order mode resonances. Fluctuations in the oversize section caused by flange misalignment and higher order mode resonances are no worse than for the straight section of WR10. The overall insertion loss of each section compares favorably to the theoretical attenuation. In Fig. 2(b), the reflection coefficients follow similar behavior. The WR10 is slightly better, but overall performance is less than −30 dB. In Fig. 2(c), reflection coefficients with an LGR on the end of a 1 m section are shown. Performance of the oversize section is significantly better than the WR10. Two-way insertion loss is nearly 5 dB less and the overall fluctuation level is smaller, achieving the theoretical goal.

[1] Mett RR, Sidabras JW, Anderson JR, Hyde JS. Hyperbolic-cosine waveguide tapers and oversize rectangular waveguide for reduced broadband insertion loss in W-band electron paramagnetic resonance spectroscopy. Rev. Sci. Instrum.(2011) 82:027107.
[2] Sporleder F, Unger H-G. Waveguide Tapers, Transitions, and Couplers, IEE Electromagnetic Waves Series, Vol. 6 (Wait JR, Billington G, Searman EDR, eds.). IEE: London, 1979.