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High Power Squeeze Type Phase Shifter at W-Band*

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Abstract

We describe the design, fabrication and bench-study of a mm-wave phase-shifter employed as a high power recirculator for a traveling wave resonator circuit. The OFE copper phase shifter was prepared by electro-discharge machining. Measured phase-shifter characteristics are presented and compared with theory. The phase-shifter was employed in a traveling wave circuit at 91.4 GHz with circulating power of 0.2 MW and subjected to fields greater than 10 MV/m without evidence of breakdown.

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High energy physics requires ever more compact charged particle accelerators, employing ultra-high electric field gradients, in excess of 100 MV/m. Recent experiments at X-band indicate that such fields are difficult to maintain due to breakdown, field emission, and damage from pulsed heating [1]. To surpass the 100 MV/m barrier, it has been suggested that miniature accelerator structures, scaled up in frequency to W-band, may permit reliable operation. To access the 100 MV/m range in the laboratory, the absence of a high power W-band source has motivated tests on an accelerator beamline, in what is essentially a relativistic klystron configuration as seen in Fig. 1(a). In such a configuration, with the 0.5 A, 300 MeV, X-band bunched beam available in our laboratory, it is possible to achieve 10 MV/m fields in a single W-band resonator [2]. However, to achieve another order of magnitude in peak field, to reach the 100 MV/m level, we require either a long transfer structure, with attendant tight tolerances in fabrication and assembly – or, a short structure, but with recirculation of power from the output to the input. The choices are illustrated in Fig. 1. Recirculation in this fashion benefits from a phase-shifter, as the power developed in the circuit depends on the phase-length of the recirculator arm. Commercial components are not adequate for such work, where vacuum compatibility and high peak power are concerns. In this work we describe the design, fabrication and bench test of a squeeze-type phase-shifter suitable for the circuit of Fig. 1(b).

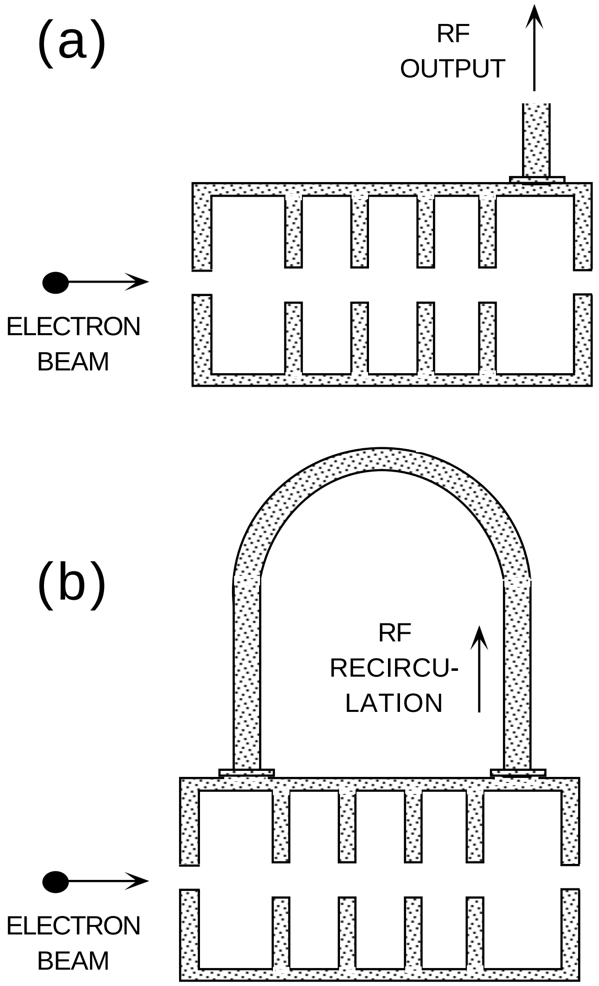

Fig. 1. Configurations for W-band power generation.

The squeeze type shifter we envision is that pictured in Fig. 2, consisting of a length of WR10 waveguide, with standard WR10 inner and outer dimensions (a=0.10", b=0.05" and A=0.18", B=0.13" outer), and single mode propagation in the range 59-118 GHz.

The waveguide can be compressed in the wide (a) dimension to provide a phase-shift. The actual waveguide will be bent to form a U-shape, meanwhile, the phase length may be understood from the scaling for straight WR10. Changing the width of the waveguide changes the guide wavenumber, β, and therefore the phase length of the guide.

$$\phi = \int_0^L \beta ds \tag{1}$$

$$\beta = \frac{2\pi}{\lambda}\sqrt{1-\left(\frac{\lambda}{2a}\right)^2} \tag{2}$$

where a is the broad wall dimension and λ the free space wavelength at the desired frequency.

For small deviations δa in the waveguide width, the change in phase length is

$$\Delta\phi = \frac{\pi^2}{a^3\beta}\int \delta a(s) ds \tag{3}$$

where s is arc length around the phase-shifter as seen in Fig. 2. The variation δa is a function of distance from the

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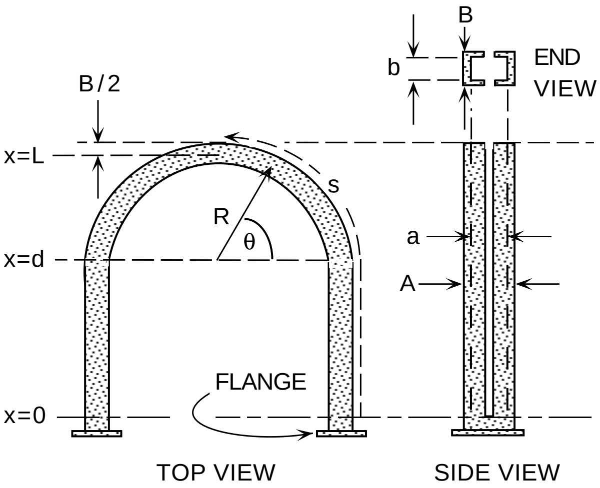

Fig. 2. Sketches of the squeeze-type phase-shifter, not to scale, showing radius of curvature R, waveguide inner dimensions $a \times b$ and outer dimensions $A \times B$.

cut, x, and has an end point deviation of Δa

$$\delta a(x) = \frac{\Delta a}{2}\left[3\left(\frac{x}{L}\right)^2 - \left(\frac{x}{L}\right)^3\right] \tag{4}$$

The geometry, coordinates and dimensions are shown in Fig. 2. Integrating, we find the phase length deviation of the U-shaped phase shifter as a function of Δa, and guide dimensions

$$\begin{aligned}\Delta\phi &= \frac{2\pi^2}{\beta a^3}\left(\int_{x=0}^{d}\delta a(x)\,dx + R\int_{\theta=0}^{\pi/2}\delta a(d+R\sin\theta)\,d\theta\right)\\ &= \frac{\pi^2\Delta a}{\beta a^3 L^3}\left(\frac{3}{4}d^4 + (1+\pi)Rd^3 + \left(\frac{3\pi}{2}+3\right)R^2d^2 \ldots\right.\\ &\quad\left. + 6R^3d + \left(\frac{3\pi}{4} - \frac{2}{3}\right)R^4\right) \end{aligned} \tag{5}$$

where $L = d + R$, with $R = 0.5$" and $d = 1.76$". The total phase length through the arm is calculated by integrating the wave number over the length of the arm and adding the perturbation $\Delta\phi$ from Eq. 5.

Meanwhile, as for mechanical considerations, the necessary force required for the deflection Δa is

$$F = -\frac{3EI_y}{L^3}\Delta a \tag{6}$$

where $E \approx 1.17 \times 10^{11}$ N/m^2 is Young's modulus for OFE Cu, and the moment of inertia of the cross-section is $I_y \approx (AB^3 - ab^3)/12$. With this one may show that the maximum stress on the copper is

$$\sigma_{\max} = -\frac{3EB}{4L^2}\Delta a. \tag{7}$$

To prevent plastic deformation of the waveguide and hence maintain repeatability, we avoid stressing the guide more than 5% of its yield strength, $Y \approx 6.9 \times 10^7$ N/m^2.

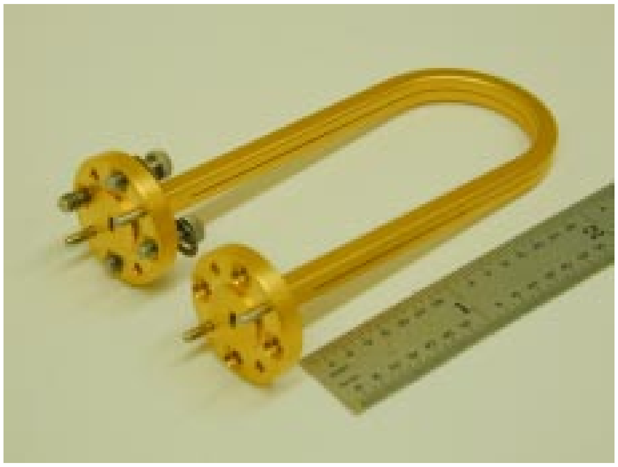

Fig. 3. Picture of prototype phase shifter (scale in inches).

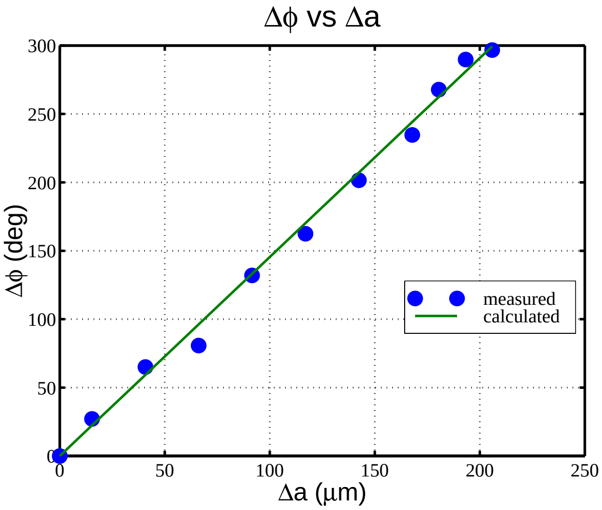

Fig. 4. Measured points overlayed with analytical calculation.

With these design scalings in hand, we fashioned a phase-shifter using a 8" length of extruded OFE copper, with interior dimensions as for WR10. A slit was cut through the broad wall by EDM to facilitate squeezing, and 304L stainless steel flanges were furnace brazed using CuAu 90/10 alloy. The finished assembly seen in Fig. 3 was then chemically cleaned as this has been found in waveguide studies to remove any zinc or other unwanted material from re-deposit during the EDM process and substantially reduce attentuation.

We characterized the S-matrix for this device under low power using a W-band vector network analyzer (VNA) [3]. We took VNA measurements for a series of values of Δa with the help of a stack of feeler gauges used to control the slit gap. The data are summarized in Fig. 4 showing the phase shift versus Δa at 91.4 GHz. The calculated phase shift from Eq. 5 is plotted with the measured data in Fig. 4, giving good agreement. The insertion loss seen in Fig. 5 is a factor of 2.7 worse than the theoretical result for straight TE_{10} mode attenuation in OFE WR10, given by

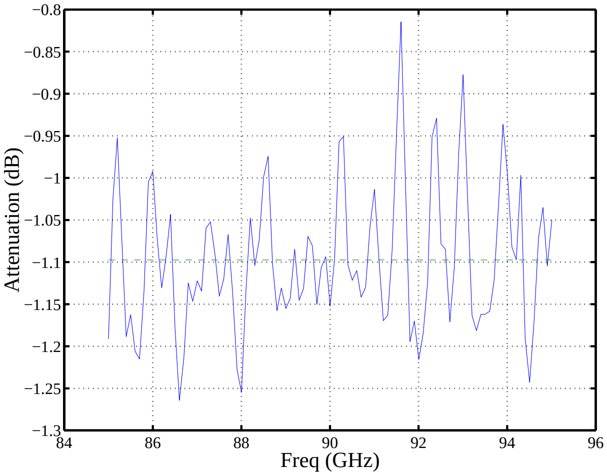

Fig. 5. Attenuation through the phase shifter/recirculator versus frequency. The average attenuation is -1.1 dB.

TABLE I

Field levels in WR10 and WR90.

E(MV/m)	P(W) - WR10
0.8	1.00E+03
2.5	1.00E+04
7.8	1.00E+05
24.7	1.00E+06

E(MV/m)	P(W) - WR90
0.9	1.00E+05
2.8	1.00E+06
8.9	1.00E+07
28.1	1.00E+08

$$\alpha = \frac{R_s}{Z_0}\left[\frac{\omega^2}{c^2}\frac{1}{b} + \frac{2\pi^2}{a^3}\right]\frac{c}{\omega}\frac{1}{\beta}, \tag{8}$$

where $R_s = 0.073\Omega$ at the operating frequency of 91.4 GHz and $Z_0 = 377\Omega$ is the impedence of free space. The disparity between theoretical and measured we attribute to surface roughness and loss in the waveguide slit.

We tested this device in a traveling wave resonator circuit, as in Fig. 1(b), at power levels above 180 kW giving field levels above 10.5 MV/m for 100 ns for several million pulses at 10 Hz with no sign of breakdown. Table I shows the field levels for different power levels in WR10 and WR90 waveguide to illustrate the power required for testing under high fields at W-band compared with X-band. Tests at X-band producing equivalent fields would require 2 MW of power. The authors would like to thank O. Millican and D. Shelly for their expert assistance in fabrication of the phase shifter.

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