

HIGH POWER MITER-BEND FOR THE NEXT LINEAR COLLIDER

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Abstract

In the design of the Next Linear Collider (NLC), it may be necessary to transmit very high power levels (hundreds of megawatts) of microwave radiation over distances of tens of meters. The microwave transmission system will require the use of oversized waveguides and higher order modes in order to either avoid breakdown or to optimize the microwave system properties. We have studied one critical component of the proposed waveguide transmission system, namely a miter-bend for the TE_{01} mode capable of transmitting over 600 MW of power at 11.424 GHz. The miter-bend is a quasi-optical 90-degree bend. The design is based on previous, successful designs of miter-bends for high average power gyrotrons at frequencies of 35 GHz and above. The design consists of a profiled mirror and two oversized rippled-wall mode converters optimized to provide less than 0.1 dB operating mode losses.

1 INTRODUCTION

In the NLC Test Accelerator built at SLAC, the pulse compressor SLED-II producing 200 MW, 250 ns, 11.424 GHz pulses has been designed and successfully tested [1]. This pulse compressor contains the following microwave components capable of handling 60 MW pulses: circular waveguides operating at the TE_{01} mode, a magic tee, and a flower-petal TE_{10} to TE_{01} mode transducer [2]. To make a 90-degree bend of the circular waveguide TE_{01} mode transmission line, two flower-petal transducers and the rectangular waveguide bend are used. To operate at high powers, a bend of a ridged circular waveguide of a 4 cm diameter has been proposed [3]. However, such a design cannot be used with a 12 cm diameter waveguide because of sufficient conversion of the TE_{01} mode into spurious modes and, as a result, breakdowns.

The Delay Line Distribution System (DLDS) as a pulse compressor for NLC is under design at SLAC to enhance the peak power up to 600 MW [4]. We propose a quasi-optical miter-bend which can be used with a 12.7 cm circular waveguide in DLDS. This design is based on the developments of miter-bends for the 35 GHz TE_{01} mode circular waveguides [5], and for the 110 GHz HE_{11} mode corrugated waveguides [6] employed to transmit to long distances the radiation of high power gyrotrons.

2 MITER-BEND DESCRIPTION

In the quasi-optical miter-bend, we employ two circular waveguide sections cut under the angle of 45° and placed such that the waveguide axes form an angle of 90° . These waveguides are optically connected using a mirror (Fig.1). The waveguide wall goes all the way to the mirror. This eliminates diffraction expansion of the mode in the direction perpendicular to Fig.1. The mirror is profiled to compensate for the diffraction in the plane of Fig.1.

An unusual feature of the proposed miter-bend is that the operating mode is a mixture of waveguide modes. It is known that the diffraction of the TE_{01} mode at an open end of the waveguide is small compared to that of the other modes since the electric field is zero at the wall. Nevertheless, the mixture of the TE_{01} and TE_{02} modes forms not only the zero field but the derivative of the electric field equal to zero at the junction of the waveguide and the mirror. This allows to reduce diffraction [5,6]. By this reason, we introduce two periodic rippled-wall waveguides (mode converters) converting the TE_{01} mode into the optimum mixture of the TE_{01} and TE_{02} modes (Fig1.).

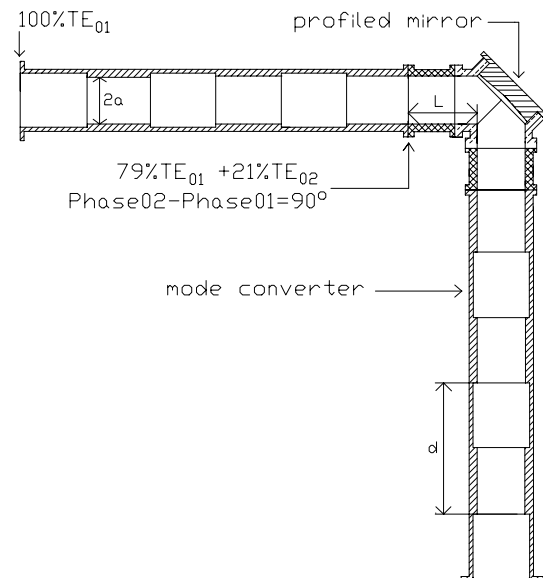


Fig.1. Miter-bend schematic.

3 MITER-BEND DESIGN

We design the miter-bend for the waveguide of the radius $a=6.35$ cm, which is oversized at the frequency of 11.424 GHz. Therefore, a quasi-optical approach, valid if $ka \gg 1$ (k is a wavenumber), can be employed for calculations. Within this approximation, the mirror is represented as a thin phase corrector. The equivalent quasi-optical schematic includes the waveguide cut by two 45° planes and the phase corrector placed as shown in Fig.2.

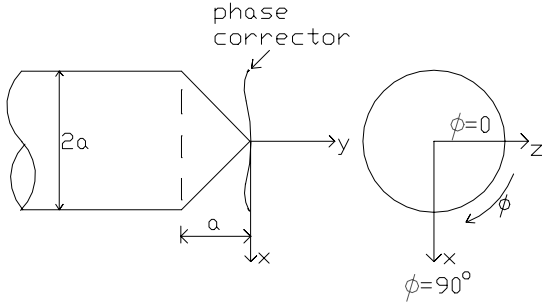


Fig.2. Quasi-optical schematic.

3.1 Diffraction Losses

The procedure of numerical calculation is the following. We take an initial field distribution as a superposition of the TE_{01} and TE_{02} modes and propagate it through the gap of the length of a to the plane of the phase corrector. In the direction $\phi=0$ (Fig.2) at the corrector, the incident electric field is the waveguide field distribution over radius r :

$$E_{\phi=0}^{inc} = \sum_{n=1,2} \frac{A_{0n}}{\sqrt{R_{0n}}} \frac{J_1(X_{0n}r/a)}{aJ_0(X_{0n})} \exp(-jkR_{0n}a)$$

where A_{01} and A_{02} are amplitudes of the TE_{01} and TE_{02} modes, $X_{01}=3.832$, $X_{02}=7.016$, and

$$R_{0n} = \sqrt{1 - (X_{0n}/ka)^2}$$

In the perpendicular direction $\phi=90^\circ$ (Fig.2), the incident electric field distribution varies due to the diffraction and is expressed as follows [6]:

$$E_{\phi=90}^{inc} = \sum_{n=1,2} \frac{A_{0n}}{\sqrt{R_{0n}}} X_{0n} \times \int_0^\infty \frac{\gamma a J_1(\gamma a) J_1(\gamma r)}{(\gamma a)^2 - X_{0n}^2} \exp(-j\sqrt{k^2 - \gamma^2}a) d\gamma$$

To calculate the diffraction losses we represent the latter field distribution as a mode series of the waveguide of the radius a , propagate it back at the distance of a using the same integral transformation, and again express the result as a superposition of the TE_{0n} modes. The relationship between the initial amplitudes A^{ini} and the receiving amplitudes A^{rec} gives the efficiency of the miter-bend:

$$\eta = \frac{1}{2} + \frac{1}{2} \frac{|A_{01}^{rec}|^2 + |A_{02}^{rec}|^2}{|A_{01}^{ini}|^2 + |A_{02}^{ini}|^2}$$

Here we use the fact that a half area of the gap is covered by the waveguide wall (Fig.2), so the diffraction losses are twice smaller than those for the uncovered gap.

3.2 Mode Converter

We specify the amplitudes A_{01} of TE_{01} mode and A_{02} of TE_{02} mode to minimize the diffraction at the mirror aperture. A smaller diffraction at the mirror can be obtained if $(d/dr)E^{inc}=0$ at the $r=a$, at the corrector (Fig.2). This gives the amplitude ratio $A_{02}/A_{01} = -(R_{02}/R_{01})^{1/2} X_{01}/X_{02} = -0.51$ at the corrector, and $A_{02}/A_{01} = 0.51 \exp(j\alpha)$ at the distance of a from the mirror, where $\alpha = \pi - k(R_{01} - R_{02})a = 110^\circ$.

This amplitude ratio corresponds to 79% of power in the TE_{01} mode and 21% of power in the TE_{02} mode. To convert the pure TE_{01} mode into this mixture, the periodic waveguide section (Fig.1) of the following geometry can be used: period $d = 2\pi / (k(R_{01} - R_{02})) = 32.6$ cm, total length Md , where $M \geq 3$ is the number of periods, the step of the waveguide radius is

$$\varepsilon = \frac{a}{M} \frac{X_{02}^2 - X_{01}^2}{X_{01}X_{02}} \frac{\sqrt{R_{01}R_{02}}}{R_{01} + R_{02}} \frac{\arctan 0.51}{\pi}$$

Thus, for $M=3$, $\varepsilon=0.2$ cm.

The phase of the TE_{02} mode is of 90° ahead of the phase of the TE_{01} mode at the output of the mode converter. Therefore, to get these modes in phase at the mirror, we insert a waveguide section such that the length between the mode converter and the mirror is $L=0.75d$ (Fig.1).

3.3 Mirror Profile and Efficiency

The incident electric field at the corrector can be written in coordinates (x, z) of Fig.2 as follows:

$$E^{inc}(x, z) = \frac{1}{2} (E_{\phi=0}^{inc} + E_{\phi=90}^{inc}) + \frac{1}{2} (E_{\phi=0}^{inc} - E_{\phi=90}^{inc}) \cos\left(2 \arctan \frac{x}{z}\right)$$

To calculate the mirror profile we determine the phase distribution of this field:

$$\Phi^{inc}(x, z) = \arg(E^{inc})$$

We represent the mirror surface in the coordinates (x_s, y_s) , connecting to the surface. Since the mirror is titled by 45° , the relationship between the coordinates (x_s, y_s) and (x, y) is $y = y_s / \cos 45^\circ$ and $x = x_s \cos 45^\circ$. Therefore, the profile of the mirror, to conjugate the phase, is the following:

$$y_s = \Delta(x_s, z) = -2 \cos 45^\circ \Phi^{inc}(x_s \cos 45^\circ, z) / k$$

For the mode amplitude ratio of 0.51 and the mode phase shift $\alpha=110^\circ$ determined in Sec.3.2, the numerically calculated efficiency of the miter-bend is $\eta=0.983$, which corresponds to less than 0.1 dB diffraction losses. The 3D mirror profile is depicted in Fig.3. The mirror is almost cylindrical because there is no diffraction in z -direction (Fig.2), plus the phase shift between the modes is specified to provide a flat phase front in z -direction at the mirror. A correction in x -direction is needed, and the optimum profile is plotted in Fig.4.

The simulations indicated that the efficiency varies from 0.984 to 0.980 while the ratio of mode amplitudes A_{0z}/A_{01} varies from 0.4 to 0.6 and the phase shift $\alpha=110^\circ$ remains the same. In this case, the mirror profile is cylindrical, and the losses are only due to the diffraction at the waveguide aperture.

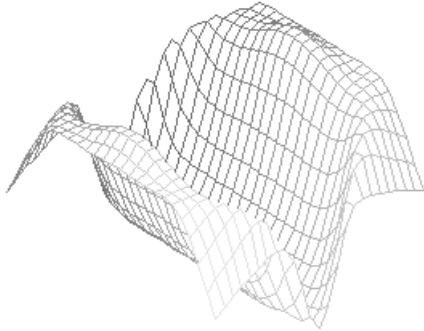


Fig.3. 3D profile of the mirror (off scale).

The efficiency can be raised up to 0.993 using optimization by α . Varying α , we minimize the diffraction at the waveguide aperture as well as at the mirror. However, there is a parasitic polarization conversion due to scattering at a non-cylindrical mirror. This effect has not been taken into account by the quasi-optical approach. The estimation indicates that the polarization losses are about 0.013, which brings the efficiency down to 0.98 .

4 CONCLUSIONS

We design a quasi-optical miter-bend for DLDS. It is capable to handle high peak power microwave pulses because highly oversized waveguides are utilized. Such a design cannot be employed with a small diameter (4 cm) waveguide, smooth bends are preferable for that.

The efficiency of the miter-bend meets the DLDS requirements. Less than 0.1 dB losses are obtained in the calculations. The mirror can be made mechanically steerable to reach maximum efficiency in a cold test. The length L of the straight waveguide section can be optimized in a cold test as well. The mode converter is designed as a periodic waveguide of the length of 3 periods, and the corrugation is rectangular.

The mode converter can be modified to employ a sinusoidal corrugation. The length of the mode converter can be lowered, though the corrugation profile should be optimized for that.

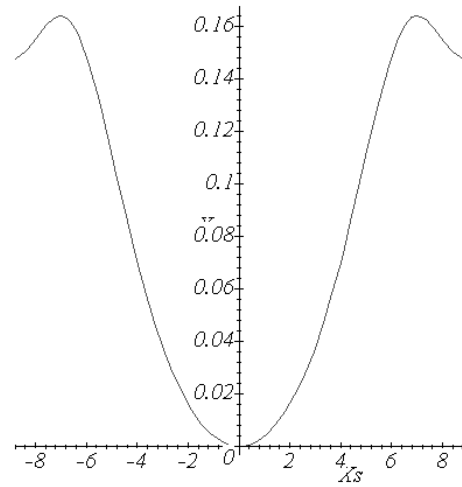


Fig.4. Mirror cut in x -direction (dimensions in cm).

5 ACKNOWLEDGMENTS

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6 REFERENCES

- [1] S.G.Tantawi et al., 'The Next Linear Collider Test Accelerator's RF Pulse Compressors and Transmission Systems', Proc. of 1997 Particle Accelerator Conference, IEEE, p.3192.
- [2] S.G.Tantawi, K.Ko, and N.Kroll, 'Numerical Design and Analysis of a Compact TE10 to TE01 Mode Transducer', Conference on Computational Accelerator Physics, Los Alamos, NM, 1993, AIP Conference Proceedings 297, p.99.
- [3] C.Nantista, N.M.Kroll, and E.M.Nelson, 'Design of a 90° Overmoded Waveguide Bend', Proc. of 1993 Particle Accelerator Conference, IEEE, p.983.
- [4] S.G.Tantawi et al., 'A Multi-Moded RF Delay Line Distribution System for the Next Linear Collider', Proc. of 1998 European Particle Accelerator Conference, p.305.
- [5] M.A.Shapiro and S.N.Vlasov, 'Study of Combined Transmission Line for High Power Wave Generated by a Gyrotron in the Millimetre Wavelength Range', International Journal of Electronics, 1992, Vol.72, p.1127.
- [6] J.L.Doane and C.P.Moeller, 'HE11 Mitre Bends and Gaps in a Circular Corrugated Waveguide', International Journal of Electronics, 1994, vol.77, p.489.