Feasability Study of Optically Coupling RF-Power at mm Waves

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Abstract

At mm-wavelengths, ordinary waveguides show considerable attenuation. Corrugated overmoded waveguides have strongly reduced attenuation, while maintaining stability by introducing the well known pattern of passbands and stopbands. Fields either transform to surface waves with very high losses, or concentrate at the center of the waveguide and propagate with very low loss. The latter, are employed to transport RF-power. Considering the field pattern, optical free space coupling to an accelerator structure, is thinkeable. We have investigated the coupling mechanism itself, e.g. field leakage and power losses to the outside and designed a device for optical coupling from a corrugated waveguide into a planar muffin-tin structure.

I. INTRODUCTION

Since the original idea came up to build particle accelerators at mm-waves, [1] intense research has been going on at Argonne and the universities of Madison, Chicago and Berlin. For an overview, the reader is referred to [2] and to numerous publications at this conference e.g. [3]. Early in the investigations, we decided to look at more detailed problems, like an rf-coupler, since the frequency band above 100 GHz leads to very different requirements and to surprisingly different designs. This fact is well demonstrated by the design process of an rf-coupler which we present below. This process starts with the choice of a corrugated and overmoded waveguide to keep losses low, and to reach the intended levels of power transport (for a rectangular waveguide typical values of attenuation would be 1 db/ft with a maximum CW-power of few kW!). Since this waveguide aperture is an order of magnitude bigger than all sizes within the structure itself, a taper is needed. Such huge geometric differences make the design difficult (how to model a periodic structure feeding another, but different periodic structure). We opted to model the structure itself with MAFIA [6] and used a mode matching technique to model the corrugated waveguide and the taper.

II. CHOICE OF THE CORRUGATED OVERMODED WAVEGUIDE

Industry [5] offers a variety of oversized low-loss components for use at high frequencies. We found the waveguides to be optimized for power transport over longer distances with extremely wide apertures. Since this does not exactly meet our situation, we decided to design our own waveguide. The following describes the procedure we carried out. We relaxed on the attenuation to reduce aperture (circular symmetry assumed), which benefited our taper design later on. We chose an aperture diameter of 0.75” rather than 1.25”. We inserted corrugations and increased their depth until we encountered a clean separation of modes with φ=1 dependence.

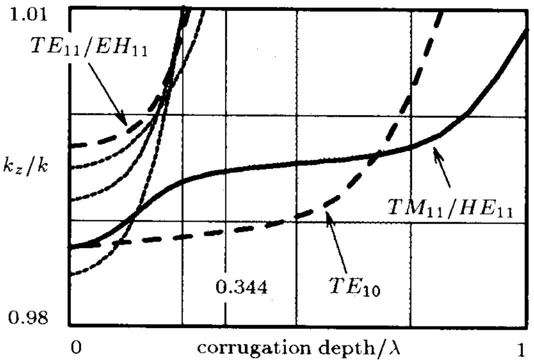

Figure 1. Normalized propagation constant versus normalized corrugation depth (f_0=120GHz, phase advance=0.73π, tolerance$\leq 10^{-4}$).

We also observed the slope of the propagation constant versus corrugation depth, which should be as low as possible, since then little field is present in the corrugations. The field is rather concentrated around the waveguide center. We obtained a whole band of possible corrugation depths at $0.3\lambda - 0.75\lambda$ (shaded region in Fig. 1). Our design tends towards the lower end at 0.344λ. Consult Table 1 for the exact dimensions.

geometry	size/mm
inner radius	9.5250
outer radius	10.3840
period	0.9144
iris thickness	0.2540

Table 1. HE_{11}-mode waveguide dimensions.

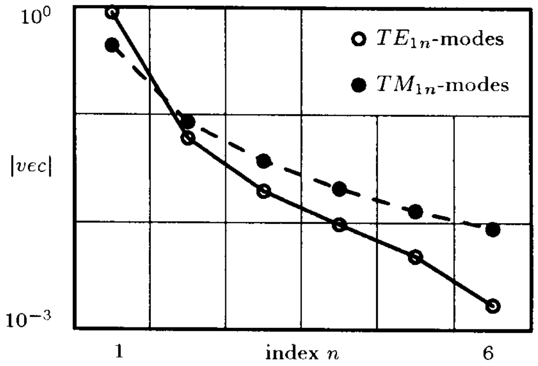

Figure 2. Absolute value of eigenvector versus index n (ϱ-dependence, $\varphi = 1$-dependence).

Calculations were done using the mode matching technique. Periodic boudaries were applied and eigenvalues and eigenvectors found after decomposing the scattering matrix into singular values (SVD). The main advantage of Singular Value Decomposition is that, it returns the eigenvectors without further computational effort. It also neatly finds all eigenvalues of multiple order. To check convergence we observed the eigenvector amplitudes decline with increasing mode order (Fig. 2). We found convergence generally to be good with few modes. Note that convergence for TM-modes is slower than that for TE-modes.

III. DESIGN OF THE OPTICAL COUPLING DEVICE

Before we design the optical coupling device we investigate the optical coupling itself. Three questions come to mind:
Which gap widths are tolerable?
What taper apertures are needed to catch the wave?
What losses, due to reflection, mode conversions and radiation, does the gap inflict?
Where the gap width is the distance to be crossed by optical coupling. The receiving or taper aperture is the aperture of the waveguide facing the corrugated guide. To answer these questions, we investigate the transmission from the corrugated waveguide to a regular (cylindrical) waveguide, and sum the transmitted power of all modes. We assume we can obtain a device that will, without further losses, combine all transmitted modes to the desired one (rectangular TE_{10}). Fig. 3 shows the sum of the amplitudes of the transmitted waves versus gap width. A gap of the order of μm will hardly inflict any losses, in the mm-range we find a minimum transmission of around 92 % and only when the gap width is comparable to the waveguide aperture, do we see serious losses (cm-range).

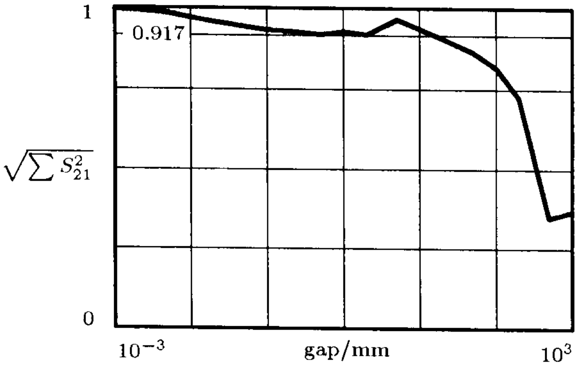

Figure 3. Sum of amplitudes (rms) of transmitted waves versus gap width (phase advance=0.73π).

Fig. 4 shows the sum of the amplitudes of the transmitted waves versus aperture of the regular waveguide. As expected, we find that, the receiving waveguide should have an aperture size close to the aperture of the corrugated one. Gap losses then converge to about 94 % with a gap width of 1 mm. Both, rather quickly obtained results lead us to think that optical coupling to a mm-wave structure is possible with a transmission of $\geq$ 90 %.

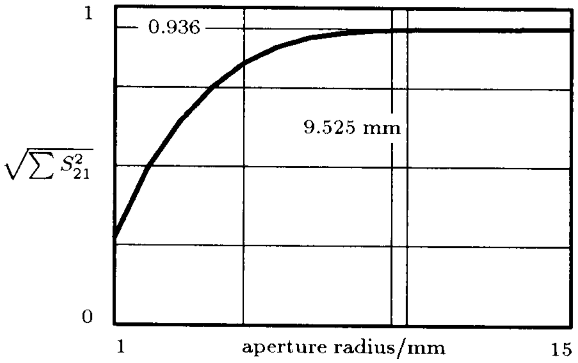

Figure 4. Sum of amplitudes (rms) of transmitted waves versus receiving waveguide aperture (phase advance=0.73π, gap=1 mm).

Carrying on, with the design of the optical coupling device we arrive at the taper section. Fig. 5 shows a scale drawing of the actual design and gives a good impression on the geometrical differences (the actual size is three times smaller!). Note that up to the last taper step we have circular symmetry, whereas the accelerating structure below is a rectangular one. From the above results (Fig. 4) we set the first taper step aperture to 0.75" = 19.05 mm. After many optimization cycles, we reached a transmission of 90 % with a gap width of 0.5 mm.

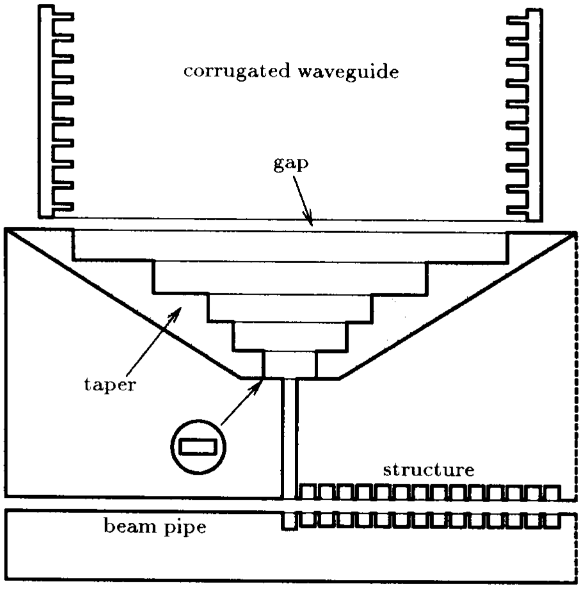

Figure 5. yz-cut of the mm-wave structure with optical coupling and taper section (scale 3:1).

According to Fig. 3, we could improve the transmission by narrowing the gap to 0.2 mm or less. We could also allow more taper steps, which certainly would enhance bandwidth. Alltogether, we hope to reach a 95 % transmission, with a more careful design. Fig. 6 shows the field pattern of the electric field inside the accelerating structure, with a matched coupler. There are two coupler cells and two regular cells. The phase advance is $2\pi/3$, as it should be. Fig. 7 zooms in on the coupler cell again displaying the electric field.

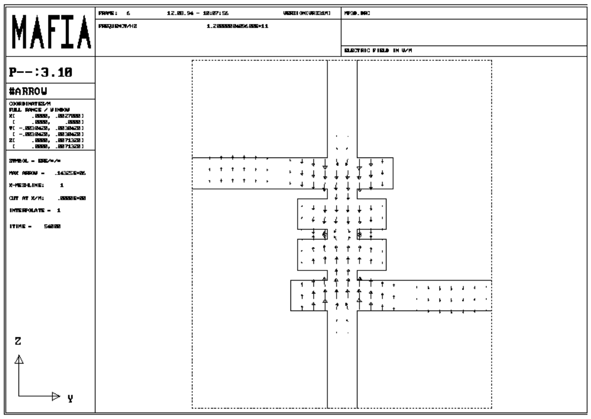

Figure 6. yz-cut of the mm-wave accelerating structure. Arrows display the electric field.

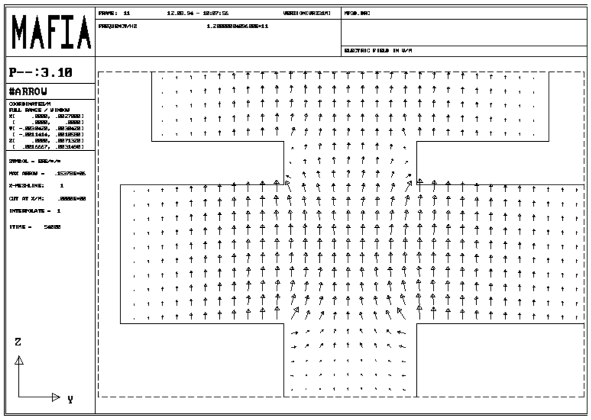

Figure 7. Zoom of coupler cell. Arrows display the electric field.

To be able to simulate the complete structure, a program (Fortran) was written that computes the scattering matrix of various waveguide cross-section jumps (rectangular, circular and mixed). This program is also able to import the scattering matrix of the accelerating structure which was computed with MAFIA. The structure was fed with the eigenvector of the HE_{11}-mode obtained while designing the corrugated waveguide. 1024 corrugations were used to approximate the infinite periodic structure. The accelerating structure, which is infinitely periodical in nature, was terminated by the coupler cell designed earlier [4]. A matched end cell indeed mimicks an infinite continuation of the preceeding structure. The design was automated by minimizing $-\log_{10}(S_{21})$ with Simulated Annealing [7] in 10 dimensions. Simulated Annealing is advantageous, since, unlike Conjugate Gradients, it will not converge into the first minimum it encounters. Instead, it will search and find the global minimum. In waveguide design, especially when geometry steps are located close to one another, there are a countless number of different (and unsatisfactory) minima.

IV. CONCLUSION

At frequencies above 100 GHz power transport is done with overmoded and, often, corrugated waveguides. This power transport system leads to the need of taper sections, but it also gives the opportunity to relax tolerances by adopting optical coupling. In an earlier publication [4] an rf-coupler was designed, which was fed from a mono-mode rectangular waveguide. The transmission thereby was as high as 98 %, but power sources should be located in immediate neighborhood to the accelerating structure, and even then, losses would be considerable, and arcing within the power transport system would be an immediate threat. The optical coupling device designed here reduces transmission to 90 %, but allows more flexibility in the positioning of components all the same. We have reason to believe that we can reach a transmission of 95 % by relatively simple measures like narrowing the gap and including more taper steps. We are confident that our design will hold to scrutinity of measurements, which we plan to engage in.

V. ACKNOWLEDGEMENT

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References

[1] H. Henke, Y.W. Kang and R. Kustom, “A mm-wave RF structure for relativistic electron acceleration”, Argonne Natl. Lab., ANL/APS/MMW-1, 1993

[2] H. Henke, “MM-Wave Linac and Wiggler Structures”, Proc. European Particle Accelerator Conf., London, 1994, vol. 1, pp. 322

[3] H. Henke, “Planar Structures for Electron Acceleration”, Proc. Particle Accelerator Conf., Dallas, 1995

[4] B.W. Littmann, M.H. Bairu and H. Henke, “A mm-Wave Coupler Design”, Proc. European Particle Accelerator Conf., London, 1994, vol. 3, pp. 2019

[5] J. Doane, “High Power Microwave Components in Oversized Waveguides”, Specifications by General Atomics, P.O. Box 85608, San Diego, CA-92186-9784

[6] The MAFIA Collaboration, F. Ebeling et al., MAFIA User Guide, 1992

[7] W.H. Press, S.A. Teukolsky, W.T. Vetterling and B.P. Flannery, “Numerical Recipes in FORTRAN”, sec. edition, Cambridge University Press, 1992, pp. 387-448