Development of an X-band Free Electron Maser Output Coupler

C. Petichakis , R. A. Stuart, C. C. Wright, A. I. Al-Shamma'a, J. Lucas, Liverpool University

We have simulated, constructed and tested a frequency dependent coupler designed to overcome mode competition problems in a waveguide free electron maser (FEM) oscillator operating in the X band range.

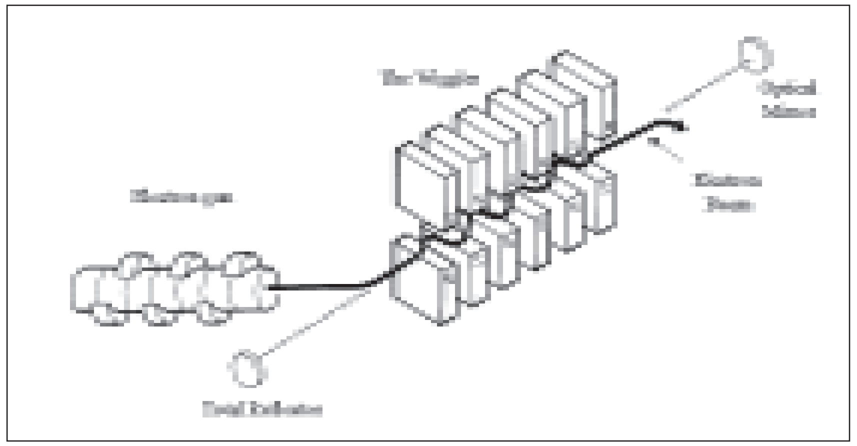

Figure 1: The electron beam passing through the Wiggler magnet.

Many high power microwave amplifiers such as the travelling wave tube (TWT) and the gyrotron operate by means of an interaction between space charge waves on an electron beam and the electromagnetic (e-m) wave to be amplified [1]. In order for the interaction to be large, it is necessary for the phase velocities of the electromagnetic wave and the space charge waves to be very close in value (synchronism). Since the phase velocity of a space charge wave is almost the same as the velocity of individual electrons composing the beam, which is usually much less than the phase velocity of the e-m wave, special measures are needed to achieve synchronism. The e-m wave can be slowed by guiding it along a spiral conductor surrounding the electron beam, as in a TWT for example [2], or spatial harmonics can be imposed on the space charge waves by spiralling the trajectory of the electrons using a longitudinal magnetic field, as in the gyrotron [3].

We have been investigating a relatively new form of device - the free electron maser (FEM) [4,5], in which synchronism between the space charge waves and the e-m radiation is brought about by "wiggling" the electron beam by means of a periodic magnetic field (Fig 1.)

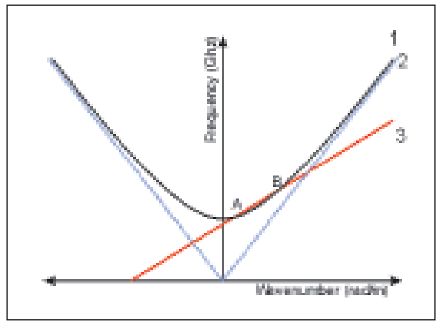

Figure 2: The dispersion curves for an e-m wave in a waveguide.
1: Waveguide dispersion characteristic
2: Radiation free space characteristic
3: Electron beam dispersion curve

Typical dispersion curves for an e-m wave confined in a waveguide and the first spatial harmonic of the space charge waves on the electron beam are illustrated in Figure 2. The slope of the electron beam dispersion line is equal to the velocity of the electrons and can be controlled by adjusting the accelerating voltage applied to the electron gun. Synchronism occurs at the intersection of these two curves, and in general there are two points where this can be achieved.

We have been investigating the FEM interaction by converting the amplifier into an oscillator by forming the waveguide into a cavity by placing "mirrors" at each end. These can be simple metal diaphragms having small holes to allow the electron beam to enter and leave the cavity (Figure 3).

Figure 3: The metal diaphragm

The build up of microwave power in the cavity from noise, when the beam is switched on, can be detected by means of a coupler - a small aperture in the wall of the cavity waveguide linking it to another output waveguide.

We have observed that during this build up process both the synchronous frequencies grow initially, but eventually one frequency dominates and suppresses the other.

Unfortunately it is normally the less desirable, close to cut off, frequency that reaches saturation first and then dominates. A similar effect has been observed in gyrotron oscillators [6].

In order to solve this problem, some means of reducing the growth rate of the close to cut off mode is necessary. In this paper we outline the use of a frequency dependent coupler having a high transmission for the low frequency mode, and a smaller coupling factor for the higher frequency. The effectively larger loss suffered by the low frequency component compared with the high, could result in suppressing the lower frequency, while allowing some of the higher frequency power to be coupled out of the cavity.

Principle of the cavity

The ideal frequency dependence of the coupler should be as shown in Figure 4, with the transition from the low to the high frequency regime occurring at 9 GHz for our FEM device.

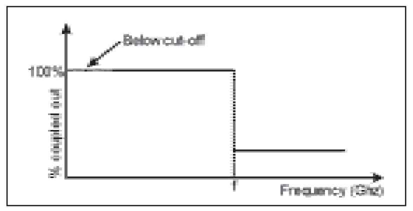

Figure 4: Frequency dependence of an ideal coupler.

For practical reasons, it was necessary to place the coupling aperture on the broad wall of the guide. To allow maximum transmission close to cut off, this aperture was chosen to be a transverse slot right across the broad face, so that the cut off frequency of the guide and the slot should be the same.

To our knowledge, we believe that a theoretical calculation of the amount of coupling through such a slot has not been attempted. Here, we assume that coupling is predominantly by means of a magnetic dipole generated by the transverse component of the e-m wave in the cavity. When the oscillator is functioning, there is very nearly a standing wave in the cavity. If the slot coupler were placed a quarter of a wavelength away from an end mirror - where there is a magnetic field node - there would be very little coupled output. If the position of the slot is chosen carefully to create a notch in transmission somewhere between the desired upper oscillation frequency and the unwanted near cut off frequency, then it should be possible to produce the differential loss required. Fig 5 illustrates the principle. For our device, the notch frequency was chosen to be 9 GHz.

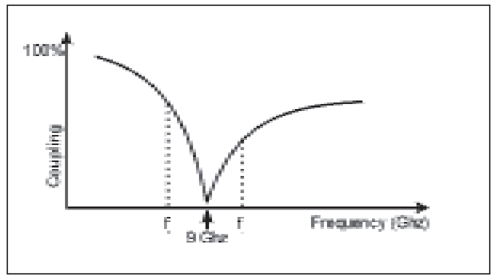

Figure 5: Notch in transmission between the two frequencies of interest.

Simulation

We have used the electromagnetic solver package CONCERTO to investigate this concept. The dimensions of the guides simulated were 19 x 10mm and the slot was positioned 17mm from the cavity mirror, a quarter of a guide wavelength at 9 GHz. A further modification of the design was incorporated at this stage. The output waveguide was also terminated at the end closest to the slot by another mirror 17mm away. This converts the output guide from a double ended to a single ended device. Furthermore at 9 GHz any power reflected by this mirror should destructively interfere with power coupled directly in the other direction, thus further improving the notch characteristics. The results of one of the simulations are shown in Figure 6.

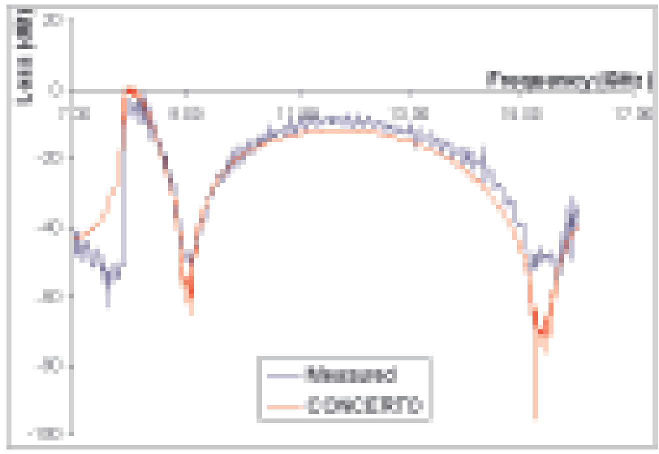

Figure 6: Calculation of power coupled out from an 1mm slot using CONCERTO.

The coupling at frequencies well below 9 GHz tends towards 100%, and was found to be practically independent of the slot width - provided this was greater than 2mm. For frequencies above 9 GHz the coupling could be adjusted to any desired value by adjusting the slot width, so that any required differential loss between the two competing modes could be achieved in theory.

Experimental results

We have constructed a coupler having the dimensions outlined above using WR75 copper waveguide. The |S| parameters of the coupler have been measured using a Marconi 6200 test set (Fig 8). The results obtained are also shown in Figure 6.

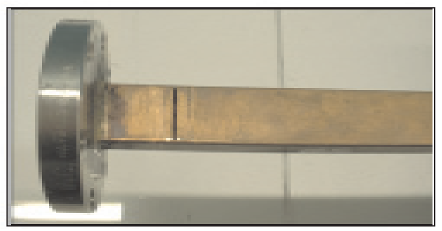

Figure 7: The coupler's 1mm wide slot.

As can be seen the agreement between the practical results and the simulation is reasonably good, although the attenuation loss in the guide and a possible small misalignment of the two mirrors relative to the slot has not been taken into account.

Summary

We have simulated, constructed and tested a frequency dependent coupler to control the problem of mode competition that occurs in waveguide FEM oscillators. The agreement between the results is satisfactory. Initial experiments using the coupler in our FEM oscillator proper indicate that mode competition can indeed be controlled in this way.

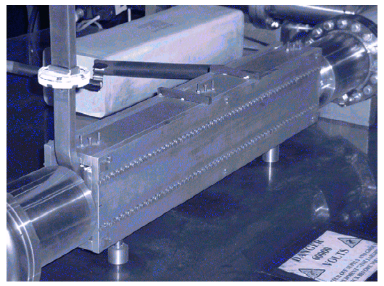

Figure 8: The wiggler magnet on the FEM.

References

[1] G. Watson, "Principles of Electron Tubes", D. Van Nostrand Company Inc. , 1965.
[2] J. F. Gittins, "Power Travelling Wave Tubes", English University Press Ltd, 1964.
[3] V. L. Granatstein, P. Sprangle, M. Hernden, P.K. Parkev and S.P. Schlesinger, "Microwave amplification with an intense relativistic beam", J. App. Phys. Vol 46, pp 3800-3805, 1975.
[4] C. C. Wright, A. I. Al-Shamma'a, J. Lucas, R. A. Stuart, Nuclear Instruments and Methods A 445, 2000, p. 197.
[5] C. C. Wright, R. A. Stuart, J. Lucas, A. I. Al-Shamma'a, Optics & Comms 185, 2000, p. 387.
[6] L. R. Bernett, L. H. Chang, H. Y. Chen, K. R. Chu, W. K. Lau, C. C. Tu, "Absolute instability competition and suppression in a millimeter-wave gyrotron travelling wave tube", Phys. Rev. Lett., vol 63, pp 1062-1065, 1989.