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**The University of Wisconsin
High-Power Microwave Transmission
and Mode Conversion Program**

Progress Report

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and

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Summary of Research Performed During the 1993-94 Fiscal Year

1. Quasi-Optical Converter Design for Varian Gyrotron SN 4.1

A quasi-optical mode conversion system for the Varian gyrotron SN 4.1 operating in the $TE_{22,6}$ mode at 110 GHz was completed. The design incorporates a two-mirror beam waveguide to lift the beam radiated by the dimpled-wall mode converter out of the bore of the superconducting magnet before the beam reaches the final two shaping mirrors. A complete set of drawings and machining code for all four mirrors (including mounting and aligning hardware required for cold testing) was provided with the final design. The design code for the mirror waveguide was also transferred to Varian. The code is quite general and allows for design at an arbitrary frequency, mode of operation, bore diameter, bore length, etc.

2. Quasi-Optical Converter Cold-Test Measurement

The prototype Vlasov converter designed for Varian gyrotron SN 4.1 was tested experimentally at low power, beginning with the field radiated from the dimpled mode converter, continuing on through to the microwave beam following the mirror waveguide, and ending with the beam reflected from the final shaping mirror. The measured results were compared with calculated patterns generated with diffraction code (actually, several separate codes cascaded) which we have developed.

The initial results of the measurements taken last fall showed some significant disagreement with theory. Far-field polar and azimuthal radiation patterns of the dimpled-wall launcher (designed and machined at Varian) were in fair agreement with theory, although some undesirable radiation structure was observed in the patterns. In addition, and more importantly, the peak of the far-field azimuthal pattern was displaced nearly 20° from the theoretical peak.

Near-field planar scans also indicated that the dimpled launcher was not performing as predicted theoretically. An 11 mm displacement of the beam along the axis of the waveguide was clearly observed. Since the results of earlier measurements of this type using a $TE_{15,4}$ dimpled launcher had shown much better agreement with theory, we began to scrutinize the experimental setup. In order to determine the frequency more accurately, a cavity stabilized 11.4 GHz Gunn oscillator was borrowed from General Atomics along with a harmonic mixer. By mixing the tenth harmonic of the stabilized source with the output of the main oscillator (also from a Gunn oscillator), we were able to verify the frequency of operation to within several hundred kHz of the 110 GHz design frequency. Simulation had shown that the bandwidth of the dimpled launcher should have been no less than two hundred MHz, so frequency was not the problem.

Several other sources of possible error were investigated (e.g., the mode purity of the low-power TE_{22,6} mode transducer designed by Charles Moeller and built at General Atomics), all without identifying a probable cause for the disagreement between experimental and theoretical results. We reserved, as a last resort, measurement of the internal surface profile, since this procedure is both difficult and expensive. Since the dimpled launcher output beam was of fair quality (although displaced) and time had begun to grow short, we decided to proceed with the measurements of the remainder of the system components.

In order to compensate for the angular and longitudinal displacement of the theoretical beam with the measured beam, the mirror system following the dimpled launcher was both rotated and translated. Again, the measured pattern of the output beam at the focal plain was, not unexpectedly, in only fair agreement with theory. It was difficult to assess the performance of the mirror system, since the input to the system (i.e., the beam radiated from the dimpled launcher) was not in good agreement with the assumed input. The original time line for this project incorporated an interval for possible redesign between cold testing of the prototype mirror system and implementation in the gyrotron of the final mirrors. **GIVEN THE PROBLEMS WITH THE DIMPLED LAUNCHER, IT WAS NOT POSSIBLE TO CONSIDER A REDESIGN OF THE PROTOTYPE MIRROR SYSTEM, OR EVEN TO FULLY AND ACCURATELY COLD-TEST THE MIRRORS TO ASSESS THEIR PERFORMANCE.**

Jeff Lorbeck traveled to Varian in mid December of 1993 to set up and install a 3-axis scanner. On the second to last day of this visit, Jeff Lorbeck, working with Jeff Neilson (the designer of the dimpled launcher), determined the cause of the poor agreement of the theoretical and experimental patterns following the converter. The converter was re-machined and, the following day, cold tested. The measured patterns were now in excellent agreement with theory, indicating that the problem had been solved. Unfortunately, because of the time constraints for the milestones of this project, a complete cold testing of the mirror system (followed by a possible redesign) was not undertaken before implementing the final copper mirrors in SN 4.1. Limited cold testing with the corrected launcher indicated that the system output was of acceptable quality for use in SN 4.1.

Other cold testing of the system with the corrected launcher included coupling the output beam through short lengths of four-inch diameter corrugated (eight inch length) and smooth-wall (six inch length) waveguide to investigate the effects of the gyrotron output waveguide on the intensity distribution of the beam. It was found that the field across the beam was substantially unchanged, indicating that, for the given waveguide dimensions, the various waveguide modes into which the beam could be decomposed had sufficiently similar wave numbers so that modal dispersion was not yet observed.

After implementing the copper mirror system into SN4.1, the prototype aluminum mirrors were returned to the University of Wisconsin in March of 1994 for complete cold testing. The results indicated that the beam was of an appropriate size in the neighborhood of the output waveguide and window

(although there was some difference between the measurements of the final copper and prototype aluminum systems), but that the E-plane was expanding more rapidly than the H-plane. This behavior was subsequently verified numerically using a far more rapid scalar diffraction code than was available during the initial design phase of the reflector system. Later designs of mirror systems will undoubtedly use the rapid scalar code to verify the expansion of the output beam. For SN 4.1, however, although the output beam dimensions allow it to exit the gyrotron, an external mirror would be required to refocus the beam before, for example, a hot-test load.

3. Modification of Geometrical-Optics Synthesized Surfaces

The fundamental assumptions required in the geometrical-optics (GO) synthesis of a quasi-optical converter system, although met for external converters, are not as well met for internal converters. Beam cross sections in the internal design are much smaller relative to a free-space wavelength than for the external converter systems leading to reduced Fresnel numbers. Hence, for an internal converter it is desirable to modify the surfaces synthesized using the GO-based method. Toward that end, the E- and H-plane curvatures of both final shaping mirrors (the mirror waveguide surfaces are found using a different approach not relying on the GO assumptions) may be perturbed from their GO-obtained values. The perturbations are incorporated directly into a diffraction code so that the effect on the output beam may easily be observed. It was found that for certain mirror configurations, the surface curvatures are not quite separable in the E- and H-plane, so that E-plane curvatures as a function of the H-plane coordinate (and vice-versa) have also been implemented. The code has been structured to allow the user to easily code for other types of surface perturbations.

An important class of perturbations we have considered allows one to begin with an input Gaussian beam and turn it into a more uniform output beam, a so-called flat-top profile. The perturbation in this case is about one and a half periods of a cosine across the surface of the second reflector. An important aspect of this work has been the consideration of the theoretical limits of the output beam shaping. The critical output beam parameters in a gyrotron flat-top output beam design are the beam peaking factor (peak to average intensity) and the percentage of power that misses the output waveguide aperture (the spill-over). We have found that the numerically synthesized results indicate that, with a simple sinusoidal perturbation, only the TEM_{10} mode will be substantially excited by the perturbation. The TEM_{10} mode is added to the input TEM_{00} mode to form the output beam. However, it is not possible to simultaneously reduce the beam-peaking factor and spill-over to arbitrary levels. This will probably require a more sophisticated synthesis approach like the diffraction synthesis described below.

The GO-based synthesis method with user specified perturbations has been used to design a proof-of-principle mirror system to give a flat-top beam output with the existing $TE_{22,6}$ Russian (dimpled) launcher and mirror waveguide. This system will probably not be fabricated because of similar work now underway for SN 4.1R.

4. Diffraction Synthesis

Jeff Lorbeck was introduced to a powerful reflector synthesis technique during his fall 1993 visit to The Institute of Applied Physics in Nizhny Novgorod, Russia. The technique, which is entirely diffraction based, allows one to obtain the required reflector-surface profiles to transform an arbitrary input field distribution to an arbitrary output distribution (to within the diffraction limit). The input to the system may even be specified as a matrix of complex field values provided by, say, another diffraction code used to calculate the scattering from an earlier component (e.g., the dimpled converter or the final mirror of the mirror waveguide). The only published literature describing the technique of which the author is aware was published in a Russian journal about 25 years ago. No English translation seems to be available.

We have undertaken several levels of sophistication in the development of the diffraction synthesis technique. The simplest systems investigated were two-dimensional, coaxial configurations. The mirrors in this case were replaced by phase correcting "lenses." The basic technique of transforming an input Gaussian to an output flat-top was demonstrated. Next, we considered a beam traveling through a two-mirror system at oblique incidence. This required turning the phase correction provided by the synthesis code into an actual mirror surface profile. The results were then verified by a separate diffraction code for which the input data consisted of the calculated surface profiles. Excellent results were achieved.

Three-dimensional systems were investigated next. We began with systems for which the beam possessed little angular divergence so that the diffraction could accurately be calculated using only a single component of the electric or magnetic field. A scalar diffraction code was thus used. The coaxial case was again developed first. Once the technique had been demonstrated, an oblique system was implemented. The results which have been achieved for transformation from a Gaussian to a flat-top are virtually indistinguishable from the diffraction limited output. This code is not just an interesting intermediate developmental step. It could be used to design the reflectors required to transform a gyrotron flat-top output into a Gaussian beam suitable for long-range transmission or injection into a corrugated waveguide.

Finally, a vector code was attempted. This code would be required if the shaping mirrors followed immediately after the dimpled launcher or the mirror waveguide, since the azimuthal divergence of the beam following these components is large. We have not yet been able to achieve the level of results with this vector diffraction code that was obtained for the scalar code. For the systems considered, the E-plane beam divergence was large while the H-plane divergence was not. Problems seem to occur only in the E-plane. This research is an ongoing effort interrupted only by the current Varian SN 4.1R design.

It should be mentioned that the scalar diffraction code can be used in its present stage of development for the internal shaping-mirror design if a mirror

following the launcher or mirror waveguide is used to first reduce the angular divergence of the beam. This approach may be used for the SN 4.1R design.

An important aspect of the diffraction synthesis work has been teaching the ideas and techniques involved to Brent Harper, a graduate student in our group. He has reproduced most of the results up until the vector diffraction code which he is currently studying.

5. Tapered Dimpled Launcher

A number of ideas have been considered in order to eliminate the self-oscillation that seems to be occurring in SN 4.1. Among these is the use of a tapered dimpled launcher. The taper would substantially lower the diffraction Q of modes which may be excited in the converter. In April, Jeff Neilson designed and fabricated a tapered converter that begins at 4% above cutoff and ends at 6% above cutoff. We modified the untapered dimpled launcher mode conversion code to allow for a varying radius and used coupling coefficients developed by Jamal Shafii to predict the output of the new, tapered converter. The numerical results were in substantial graphical agreement with those obtained by Jeff Neilson (and, subsequently, with numerical results found by Monica Blank using a third, independent set of coupling coefficients).

In May we made radiation pattern measurements on this launcher. Far-field azimuthal and polar radiation patterns of the tapered converter exhibited rather good agreement with theory. Measured near-field planar patterns also showed good agreement with theory, despite the fact that the current peaks inside the tapered converter are not quite as well formed as those in the untapered launcher. Jeff Lorbeck also observed that the aperture of the tapered launcher was cut at a suboptimal position. To improve the output of the launcher, about 12° (less than 5 mm) of the converter along its straight cut edge were removed. The measured patterns following the modification resulted in a slightly improved azimuthal radiation pattern in excellent agreement with theory. Since the output polar angle of the beam radiated from the tapered converter is within about a degree of the polar angle of the beam radiated from the 6%-above-cutoff untapered converter, the mirror waveguide designed for the untapered launcher was tried for the tapered launcher. The measured patterns in this case were also remarkably good.

The converter-radiation-pattern, mirror-waveguide, and shaping-mirror diffraction codes were also modified to allow for the varying radius of the tapered converter.

6. Work on Vlasov Converter System for Varian Gyrotron SN 4.1R

Work has begun at Wisconsin in collaboration with Varian and MIT on a Vlasov converter system for SN 4.1R using a tapered dimpled Vlasov type launcher of larger diameter than tested above.

7. Analysis of Gyrotron Spurious Modes

The entire complement of mode coupling and diffraction codes has been modified in order to consider the propagation of spurious modes along the complete converter system. For example, we analyzed the output of SN4.1 assuming that a $TE_{15,8}$ mode had been excited at a frequency of 105.8 GHz.

8. MIT Code Benchmarking

We have performed a diffraction analysis of mirror profiles provided by Monica Blank. Although our dimpled-wall converter codes are different and our choice of radiating aperture is not the same (although Monica has investigated different apertures and reports that the differences are negligible), the beam at the surface of the two shaping mirrors and an output plane are quite similar. The positions of the beam at each observation surface agree to within a millimeter or so, and the decay in the E- and H-planes are quite similar. The shape of the beams varies somewhat, but this may be due to slight differences in the field radiated by the launcher. As the entire gyrotron community is now completely aware, only a small percentage of "spurious" power can greatly affect the intensity distribution of a beam.

If a finer level of comparison is desired, Monica has agreed to send a subroutine to compute her coupling coefficients so that we are more nearly certain of launching exactly the same composition of waveguide modes.

9. Development of Low-Power Efficiency Test for Vlasov Converters

The determination of the efficiency of a Vlasov converter system cannot be done while it is operating as part of a gyrotron because it is not possible to separate the efficiency of the power generation from the efficiency of the Vlasov converter. Over the past year we have developed a method for the low-power testing of the efficiency of Vlasov converters. This is a difficult determination at low power and obtaining sufficient accuracy is a problem. However, we have made a complete set of measurements using this method and we believe that it can be sufficiently accurate with adequate calibration of short circuits used in the test.

10. Investigation of Optimal Beam Waist Size and Mode Content for Injection into a Circular and Rectangular Corrugated Waveguides

We have investigated a number of interesting questions which all involve the relation between HE_{mn} modes in corrugated circular and rectangular waveguides to Gaussian TEM_{mn} free space modes. Several of the topics that we have considered are:

- 1) What is the optimum beam waist of a fundamental Gaussian mode to optimally excite the HE_{11} mode in a circular or rectangular corrugated waveguide.

- 2) What percent of the HE_{11} mode is excited by these Gaussian modes relative to the power in other HE mode.
- 3) What is the difference in peaking factor of Gaussian beams of different waist sizes compared to HE_{11} modes.
- 4) What combinations of two or more Gaussian modes have the highest injection efficiencies into corrugated waveguides.

11. The Effect of Corrugations on Reduction of the Fields at the Wall of Waveguides

In Varian gyrotron SN 4.1 a nearly Gaussian beam is injected into a short section of corrugated circular waveguide which holds the vacuum window. This waveguide is 4" in diameter and only about 8" long with the window approximately at the center. Since the Gaussian mode injected into this waveguide has very small fields at the walls of this waveguide, the question arises as to whether the corrugations will have any effect upon the injected fields. Since corrugations tend to reduce the fields at the wall, we believe that the corrugations will further reduce the fields at the walls which is desirable to decrease the power leakage into the gap at the window. We have performed a simple preliminary experiment in a rectangular waveguide to demonstrate the extent to which corrugations tend to decrease the fields at the waveguide walls. We will expand on this study somewhat during the coming year.

12. Shipping of a Microwave Scanner to Varian and Further Microwave Scanner Development

During the early part of the last year we purchased and fabricated parts for a second microwave scanner which was then assembled. The original scanner was shipped to Varian in December (in 22 boxes). Jeff Lorbeck went to Varian to help them learn how to use it and to take some measurements with it. Although both the new UW and Varian scanners are fully functional, the software sometimes locks up after a scan or during calibration. This has been a persistent problem which we are still working to overcome.

During the last year, (after shipping the original scanner to Varian) we have also added the capability of making a circular scan and planar scans in two additional planes. We will transfer this software to Varian. During the next year, we will add a fourth degree of freedom (rotation) to our scanner.

13. Code Transferred to Varian

In addition to the set up and installation of the 3-axis scanner code, a number of other codes developed at UW-Madison have also been transferred for use at Varian. These codes include:

a. Russian dimpled launcher mode conversion code.

This code calculates the mode coupling along the length of the Russian mode converter and finds the fields over the radiation aperture of the launcher. These fields are required for subsequent diffraction analysis of the launcher. The actual coupling coefficients are found in a subroutine which may be replaced by the user (initially this subroutine had been provided by Jeff Neilson, although now we use coupling coefficients developed by -Jamal Shafii of our group).

b. Russian (dimpled)-mode-converter radiation pattern code.

This code calculates the near or far fields of the Russian mode converter over planar, cylindrical, or spherical surfaces based on a Stratton-Chu formulation of the diffraction integral. Excellent agreement between measured and calculated patterns have consistently been achieved with this code. It was on the basis of the disagreement between the measured and calculated patterns of the original TE_{22,6} Russian converter that a machining error was detected and corrected.

c. Mirror waveguide design and machining code.

This code is used to calculate the surfaces of a mirror waveguide given an arbitrary rotating mode, frequency, guide radius, and guide length. The program also produces output in suitable format to be used in the generation of code to drive machining tools.

d. Beam fitting code.

This code allows one to fit a theoretical beam to a calculated (e.g., output from a diffraction code) or measured beam in order to calculate the coupling between the two. The code also calculates the peak values, average values, and thus the beam enhancement factor (peak intensity to average intensity) of the beams which are important in output-window thermal considerations.

Publications and Presentations in 1993-94

K. Felch, T. S. Chu, H. Huey, H. Jory, J. Neilson, R. Schumacher, J. A. Lorbeck and R. J. Vernon, "Design Considerations for a 1 MW CW Gyrotron with an Internal Converter," Conf. Dig. of the 18th International Conf. on Infrared and Millimeter Waves, pp. 517-518, 1993, Colchester, United Kingdom.

B. C. Brown, J. A. Lorbeck, and R. J. Vernon, "Radiation Patterns and Optimization of Beam Excitation of Highly Overmoded Corrugated Rectangular Waveguides," Conf. Dig. of the 18th International Conf. on Infrared and Millimeter Waves, pp. 592-593, 1993, Colchester, United Kingdom.

J. A. Lorbeck and R. J. Vernon, "Recent Developments in Vlasov Converter and ECRH Transmission Systems Research at the University of Wisconsin," U.S.-Japan Workshop on RF Heating Technology, Osage Beach, Missouri, 1993.

J. A. Lorbeck, S. Rauf, and R. J. Vernon, "Development at the University of Wisconsin of Quasi-Optical Mode Conversion Systems for Gyrotrons," Conf. Dig. of the International Conf. on Millimeter and Submillimeter Waves and Applications, pp. 110-111, 1994, San Diego, California (Invited paper).

J. A. Lorbeck and R. J. Vernon, "High-Power Gaussian-Beam Reflector Waveguide for Use with a Gyrotron Quasi-Optical Mode Converter," Conf. Dig. of the 1994 IEEE AP-S International Symposium, Seattle, Washington, 1994.

J. Shafii and R. J. Vernon, "Mode Coupling in Coaxial Waveguides with Varying-Radius Center and Outer Conductors," Accepted for publication in the IEEE Trans. on Microwave Theory and Techniques.

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