LOW NOISE TRAVELING-WAVE MASER RECEIVER FOR THREE MILLIMETER WAVELENGTH

A.G. Cardiasmenos
Department of Physics and Astronomy
University of Massachusetts
Amherst, MA 01002

J.F. Shanley
Department of Electrical and Computer Engineering
University of Massachusetts
Amherst, MA 01002

K.S. Yngvesson
Department of Electrical and Computer Engineering
University of Massachusetts
Amherst, MA 01002

ABSTRACT

A traveling-wave maser amplifier, using iron-doped rutile as the active material, has been developed in the frequency range 85 - 95 GHz. The device has demonstrated stable traveling-wave maser gain over an instantaneous bandwidth of 140 MHz and is capable of operation as a low noise receiving system for radio astronomy and communication applications in the millimeter wavelength region of the spectrum. The maser device uses a newly developed hybrid transmission mode allowing for easy coupling of the maser material to the microwave circuit. The mode, termed the slot-fed image guide mode provides high slowing and filling factor and is relatively easy to match over a wide bandwidth. Increased system sensitivity of an order-of-magnitude can be expected using this device as an alternative to state-of-the-art cooled Schottky-barrier mixer receivers.

Introduction

One of the most exciting discoveries in radio astronomy has been the realization in the late 1960's and early 1970's that the interstellar space in our galaxy contains a large number of different molecules. After the initial discoveries at wavelengths of one to a few centimeters of NH_3, H_2O and CH_2O, radio astronomers quickly turned to millimeter wavelengths. Here, a large number of new molecules were rapidly detected due to the much greater optical depth obtained from the millimeter wave transitions. The early millimeter wave receivers used rather crude mixers, but the latest, and lowest-noise, version uses cooled Schottky-barrier diodes to achieve system noise temperatures at three millimeter wavelength of about 800°K [1]. Reduction of the overall system noise temperature to 100°K or less, including the atmospheric contribution, is now realizable with the development of the traveling-wave maser amplifier (TWM) described in this paper. This large reduction in total system noise temperature enables radio astronomy researchers to detect a given spectral line with a given signal-to-noise ratio in a time which is shortened by more than a factor of 60, compared to the best presently used receivers.

Active Material

The active material used in this millimeter wave maser is iron-doped rutile (Fe^{3+}-TiO_2). The energy levels of Fe^{3+} in the TiO_2 lattice are split by the crystal field and a D.C. magnetic field into a six-level system. The energy level diagram along the crystalline a-axis is illustrated in figure one and has been experimentally verified by several investigators over the years [2, 3]. It is essential in the development of TWM that the energy eigenvalues and the transition matrix elements be known. These parameters have been computed by a numerical diagonalization of the spin Hamiltonian matrix on the UMass CDC Cyber 74 computer system. The Jacobi method employing complex arithmetic was used for this. Experimentally derived values of the crystal field parameters determined by Carter and Okaya [2] were used in the computations. A program of relaxation rate measurements is also currently underway to increase the understanding of the inversion mechanism. The present operating point utilizes the magnetic field along the a-axis, with the 4-6 transition as the signal transition and the 1-3 and 3-6 transitions for pumping, for operation between 85-90 GHz, and has resulted in measured inversion ratios as high as 1.1 in some crystals. This operating point, illustrated in figure two, was the result of investigations of several operating points involving various combinations of energy levels and various crystal field orientations with respect to the external applied magnetic field. Most schemes investigated employed multiple pumping techniques, i.e., using two pump sources at relatively low frequencies (less than 140 GHz) where moderately powerful klystrons could be utilized.

The same operating point can be used over the signal frequency range of 85-95 GHz. The a(1-3) pump transition then varies from 43 to 55 GHz and the a(3-6) transition varies from 97 to 135 GHz. Magnetic field intensities of 2 to 10 kilogauss are required to operate the maser over this frequency range. The magnetic field is supplied by a superconducting magnet utilizing superconducting shields in a design similar to that of Cioffi [4]. The magnet, which was developed in cooperation with Magnetic Corporation of America, Waltham, MA, is capable of operation up to 23 kilogauss and has a uniformity of the transverse field of 0.1% over a distance of 8 centimeters in the longitudinal direction.

Microwave Circuit

The microwave circuit for the maser has been designed to couple directly into over-size rectangular waveguides. This approach significantly reduces line losses at millimeter wavelengths and is essential to an intrinsically low noise device such as a maser. Signals are brought into the maser dewar using WR-42 waveguide (dominant mode 18-26.5 GHz) propagating in the TE_{10} mode. A tapered transition from WR-42 waveguide to a ridge waveguide cross-section with very small gap between the ridges occurs at the maser structure. The ridge waveguide cross-section, shown in figure three, has an unloaded passband in the lowest order dominant ridge guide mode from 23 to 120 GHz. The unloaded loss of the ridged section and the two tapers to WR-42 oversized waveguide is less than 8 dB over the range from 70 - 120 GHz. Only minor mode conversion resonances have been observed and are not a significant problem in transmission of the signal or pump frequencies through the system. The maser material has a dielectric constant $\varepsilon_{\parallel} = 256$ and $\varepsilon_{\perp} = 160$ at helium temperatures and is loaded into the ridged section of the maser structure in a carrier package illustrated in cross-section in figure four. The carrier package has been developed to create suitable conditions for excitation of a mode which is basically an image guide mode fed from the slot of the ridge waveguide. Dispersion relations and impedances for this loaded system have been experimentally determined and found to correlate well with the E^y_{21} image guide mode in the frequency range of interest. A detailed analysis of this structure will be presented in a forthcoming paper [5]. Matching is accomplished through use of a quarter-wave transformer approach. An overall view of the maser structure is presented in figure five. Pump waves enter the maser through the signal output waveguide, the signal input waveguide being reserved for direct connection to the feed. An important advantage of the structure is that no separate pump waveguide circuit is required, despite the wide range of pump frequencies. Uniaxial ferrite materials of suitable composition to track the maser signal transition are utilized as isolator material to insure the gain stability of the maser.

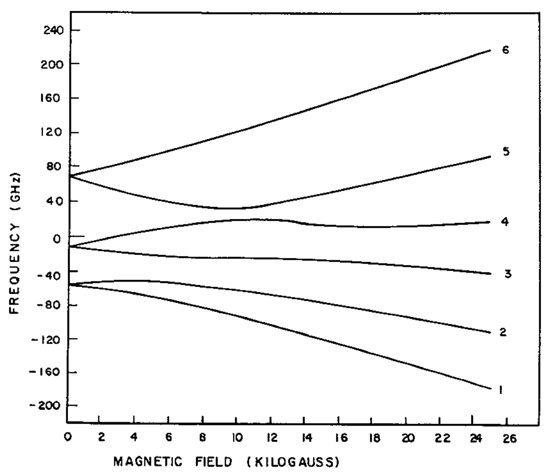

Figure One - Energy levels of TiO_2 doped with Iron along the crystalline a-axis[2]

Experimental Results

The maser has been operated successfully over the frequency range from 85 - 90 GHz. Typical electronic gain of 3 - 5 dB over bandwidths in excess of 140 MHz have been obtained in a short-length maser prototype. The length of the maser material was only 0.7 cm in these experiments and present plans call for the lengthening of the active region to produce 10 - 15 dB net gain for an operational system. Approximately 7 cm of active material could be accommodated in the structure. Using slightly longer crystal packages in recent experiments, 15 to 20 dB of gain has been realized over typically 40 to 50 MHz instantaneous bandwidths. A photograph of 4.2 dB electronic gain obtained at a frequency of 88.683 GHz with an instantaneous bandwidth of 125 MHz is illustrated in figure six. The upper trace is the operating maser gain, while the lower trace is the "cold" transmission of the maser with both pumps and the magnetic field detuned. Potential bandwidths of 200 - 300 MHz seem possible as the development of this maser device is continued. It is hoped that a finished version of this device with 10 - 20 dB net gain will be operational on the new FCRAO 13.6 meter diameter Millimeter Wave Telescope system [6], being built near Amherst, MA, by late fall 1976.

References

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[2] D.L. Carter and A. Okaya, Phys. Rev. 118, 1485 (1960).
[3] E.L. Kollberg, private communication.
[4] P.P. Cioffi, J. Appl. Phys. 33, 875 (1962).
[5] A.G. Cardiasmenos, J.F. Shanley, and K.S. Yngvesson, "A Prototype Traveling-Wave Maser Amplifier for 85 - 90 GHz Using a Slot-Fed Image Guide Slow-Wave Circuit," submitted to IEEE Trans. on Microwave Theory and Techniques, Special issue on millimeter waves, November 1976.
[6] A.G. Cardiasmenos, G.R. Huguenin, and K.S. Yngvesson, Fifth European Microwave Conference, Hamburg, 1975.

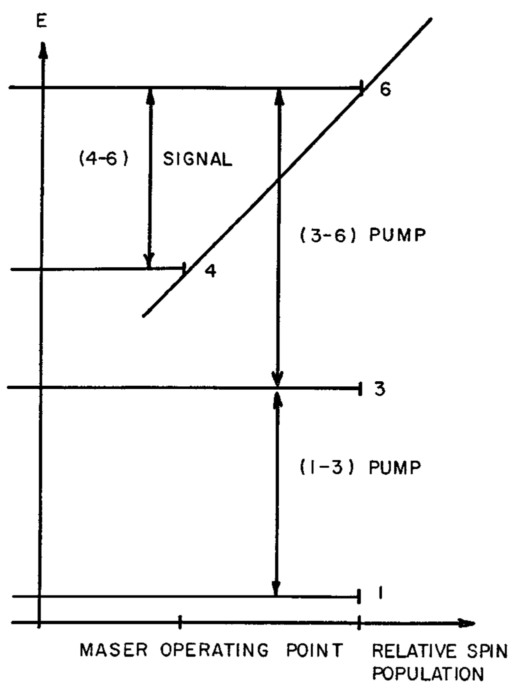
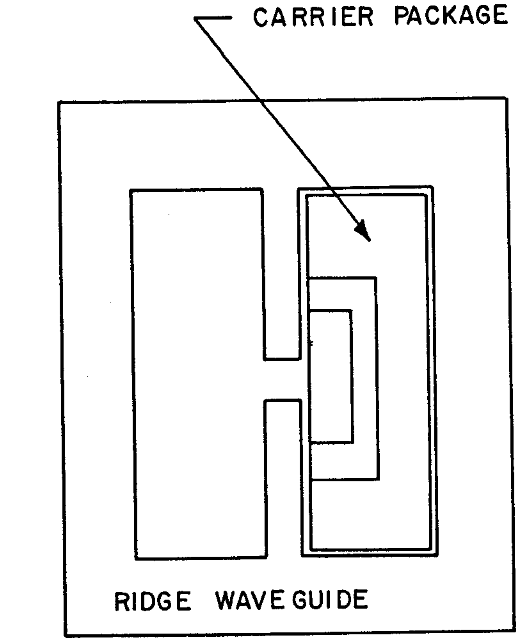


Figure Two - Operating point for the 85 - 95 GHz Maser Amplifier. Levels two and five are omitted for simplicity.



CROSSECTION-LOADED MASER STRUCTURE

Figure three - Crossection through center of Maser Structure.

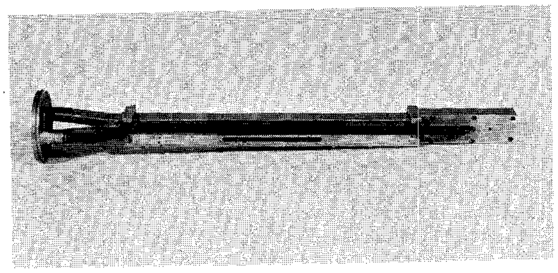


Figure Five - Photograph of maser structure. The removable side panel into which the maser carrier packages are inserted is visible in the center of the side wall of the maser structure. The tube running down the side of the maser structure is the helium fill line.

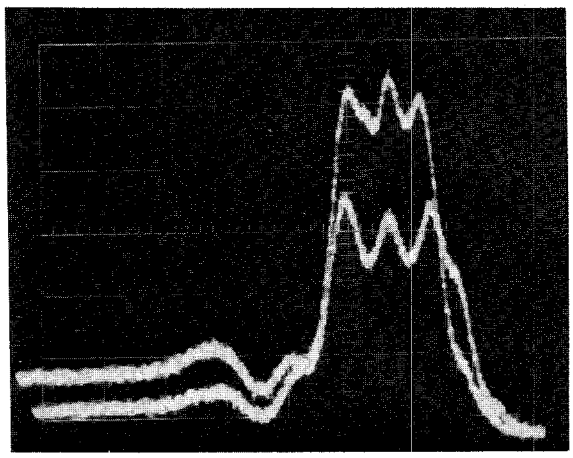
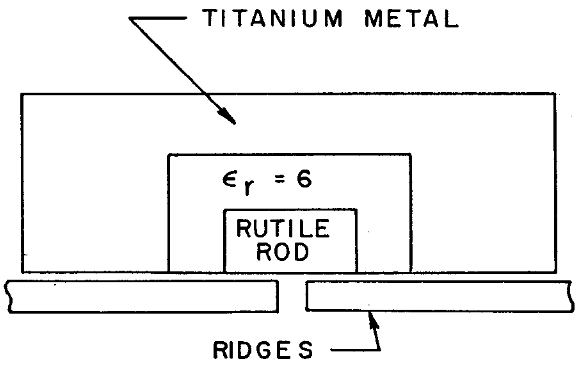


Figure Six - 4.2 dB Electronic Gain measured in an experiment with a prototype (short length) carrier package. Later experiments with longer carrier packages have demonstrated sufficient electronic gain for an operational system.



3 mm MASER SLOT-FED IMAGE GUIDE CARRIER PACKAGE

Figure Four