Low-noise 86–88-GHz traveling wave maser

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A traveling wave maser using iron doped rutile \((\text{Fe}^{3+}:\text{TiO}_2)\) has been developed for a signal frequency of 86–88 GHz. The 3-dB bandwidth is 40–50 MHz for an electronic gain of 36 dB and a net maser gain of 15–20 dB. Hexagonal aluminum substituted strontium ferrite was used for isolation. A unique overmodeled ridge guide structure is used to match pump and signal power to the active material from 30 to 120 GHz. The maser noise temperature has been measured as \(T_{\text{maser}} = 20 \pm 10 \text{ K}\).

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We have developed a maser amplifier in the frequency region 86–88 GHz with high gain and large bandwidth. The active material is iron-doped rutile \((\text{Fe}^{3+}:\text{TiO}_2)\), a single crystal which can be artificially grown\(^1\) and diffusion doped with iron. This maser obtains the largest gain bandwidth product to date at this frequency and is capable of operation close to the quantum noise limit.

Because masers are intrinsically and in practice the lowest noise amplifier available, there is at present considerable emphasis on traveling wave masers for use in radio astronomy. Previous work on iron-doped rutile for these frequencies has been carried out in our laboratories and reported by Cardiasmenos et al.\(^1\). Traveling wave masers from 20 to 35 GHz based on iron-doped rutile have been used on the 20-m telescope at the Omsala Space Observatory.\(^1\) At 25 GHz and below, ruby has been the most widely used active maser material. The systems are in use at several observatories.\(^2,3\) Development work to extend the use of ruby to 40–60 GHz is underway at these laboratories (including our own), but at higher frequencies rutile or other materials with large zero-field splitting must be used to keep transition probabilities and magnetic field strengths within usable limits.

Other devices being developed for low-noise receivers are predominantly nonlinear elements used as mixers. Impressive SSB mixer noise temperatures have been obtained for cooled Mott diodes\(^4\) \((T_M = 200 \text{ K}, L_c = 7 \text{ dB})\). Josephson junctions have received much attention for many years, but due to unexpected stability problems and unwanted nonlinearities, the noise is often many times the quantum limit.\(^5\) Nevertheless Taur and Kerr\(^6\) have developed a receiver which promises to be competitive with the cooled diode mixer at 115 GHz. An offspring of the Josephson junction work has been the quasiparticle mixer, a superconducting tunnel junction biased at the band gap. At 115 GHz Dolan et al.\(^7\) have obtained a mixer temperature \(T_M \approx 100 \text{ K}\). These devices appear to be capable of quantum noise limited mixing, but the large conversion loss \(L_c = 10 \text{ dB}\) is at least partly inherent at high frequencies.\(^8\) Receiver noise temperatures of these three types of mixers are all in the range 200–500 K, so there is considerable improvement possible for a device which approaches the quantum noise limit \((T_N = h\nu/k \ln(2) = 7 \text{ K at 100 GHz})\) as masers consistently have done. The measured noise temperature of the \(\lambda\) 3.4-mm maser reported here is \(T_M = 20 \pm 10 \text{ K}\). This ultra-low-noise contribution promises atmospheric limited observing systems for radio astronomy \((T_{\text{sys}} = 50–100 \text{ K})\) and even lower noise for laboratory or space-based applications.

The energy levels of \(\text{Fe}^{3+}\) employed for inversion are discussed in detail by Cardiasmenos et al.\(^1\). Three pumps are used at approximately 30, 45, and 113 GHz for a signal frequency of about 88 GHz. It is therefore necessary to use a structure in which the lowest frequency will propagate and still couple the signal to only the fundamental mode. An additional requirement is a region of circular polarization in the structure so that a ferrimagnetic material can be placed there to suppress the gain in the reverse direction. Without this isolation small input and output reflection would easily produce large loop gain and oscillation.

A structure satisfying these criteria is shown in Fig. 1. The very small dimensions of this dielectric loaded waveguide are necessitated by the high dielectric constant of rutile \((\varepsilon = 100)\). If the rutile crystal were somewhat narrower, only one mode of propagation would exist from 30 to 100 GHz, but it was found that a slightly overmodeled structure could be used. Oscillation in the higher modes was suppressed since the isolator couples to these modes as well.

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\(\text{FIG. 1. Cross section of the active region of the } \lambda \text{ 3.4-mm maser, showing the crystal package and how it is held in the "split block" structure.}\)
To match the pump and signal frequencies to the active dielectric loaded waveguide, a tapered ridge guide matching structure is used at one end. This end is the signal output and the pump input. The signal is matched to the input with a reduced height section of waveguide. This structure is shown with the top removed in Fig. 2. The center narrow channel is filled with the rutile package shown in cross section in Fig. 1. Reflected power for all pumps is less than $-7$ dB and for the signal it is typically $-10$ dB from either end. Insertion loss of the signal at $4$ K is $15-20$ dB.

The ferrite used for isolation must be resonant at the maser signal frequency and magnetic field, about $4$ kG. Either barium or strontium hexagonal ferrites can be used because of the large anisotropy field which can be adjusted by aluminum substitution. Reverse isolation of better than $60$ dB has been obtained, insuring unconditionally stable amplification up to very large gain.

The maser structure shown in Fig. 2 is mounted in a liquid helium Dewar with input and output reaching room temperature via overmoded stainless steel waveguide. An attenuator is placed in the input at the bath temperature to provide a cold load for noise measurements. The helium reservoir is pumped to reach $1.6$ K to achieve the highest gain. Following the maser is a standard room-temperature mixer receiver.

The electronic gain versus frequency is shown in Fig. 3. The highest frequency pump is frequency modulated in this recording, which accounts for the asymmetric line shape. The pump power required for saturation is typically a few hundred milliwatts. The recorded gain of $36$ dB corresponded to a net gain of $16$ dB and an inversion ratio $I = -1.3$ for this $4.5$-cm-long sample.

Included next to the maser package is a small iron bead which produces a magnetic field perturbation in a region about $4$ mm long. This bead is moved mechanically along the length of the maser to determine the contribution to the gain of all parts of the maser crystal. In this way we can be sure that the gain is uniformly distributed along the length as it should be for a traveling wave maser. This technique is also useful in evaluating crystal quality.

The noise contribution from the maser was measured by inserting a $1.6$-K load at the input. This method was checked by $300$- and $77$-K loads using measured input attenuation. The maser noise temperature was found to be $T_{\text{maser}} = 20 \pm 10$ K. We are presently working to reduce the uncertainty in this measurement to see if there are significant noise sources other than spontaneous emission which predicts $T_{\text{maser}}$ (theory) $= 10$ K.

In order to reduce the second-stage contribution to the noise temperature to a negligible value, more gain is required than has been obtained so far. The straightforward approach is to increase the active length of the maser. It is possible to nearly double the present length with available rutile boules, although the crystal quality has not yet been examined on that scale. Still, a net gain of $25-30$ dB may not be unreasonably expected. This should be sufficient to produce a total receiver noise temperature $T_{\text{rec}} < 100$ K.

The noise temperature measured for the maser is by far the lowest of any competitive device in the $\lambda 3-4$-mm band. It appears that quantum noise limited system temperatures will soon be available for application in astronomy, spectroscopy, and communications in the near millimeter. The principles of maser operation can be extended into the submillimeter if the demand exists, however, materials studies would be required for these higher frequencies.

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Our material was obtained in boule form from Hrand Djehirdjian, Switzerland.
Tunable single-longitudinal-mode operation of an injection-locked TEA CO$_2$ laser

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Tunable single-longitudinal-mode operation of a transversely excited atmospheric (TEA) CO$_2$ laser has been achieved using an injection technique with a cw waveguide laser as the master oscillator. Tunability in excess of 300 MHz from the CO$_2$ line center is reported for various CO$_2$ lines. A high resolution spectrum of an ozone absorption feature has been recorded using this technique.

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Various techniques have already been proposed to achieve single-longitudinal-mode (SLM) operation of a TEA CO$_2$ laser, such as, (i) injection locking techniques using low-pressure cw CO$_2$ lasers as the master oscillator, or hybrid configuration systems, both restricted to an emission frequency within a few tens of megahertz from the line center, and (ii) use of an intracavity etalon or intracavity selective absorbers, allowing tunability of the output frequency, but resulting in a reduction of laser power in the first case and a limitation of the tuning range to the width of a given absorbing gas in the latter case. The purpose of this letter is to describe a new injection technique using a cw waveguide laser as the master oscillator, which leads to continuous tunability of the TEA frequency over the pressure dependent gain bandwidth of the waveguide laser. This can be extended to above 1 GHz, which is to be compared to the 3–4 GHz gain bandwidth of a single-line TEA laser (FWHM). As compared to other tuning techniques, the main advantages are the lack of reduction in the available power of the TEA laser and the possibility of precisely controlling its output frequency by monitoring the cw injected signal heterodyned against a low-pressure laser as the local oscillator.

A TEA CO$_2$ laser with MHz linewidth and continuous tunability over GHz frequency regions about each CO$_2$ transition frequency is of particular interest for high-resolution spectroscopic studies, as the SLM output of the high-power TEA laser can be tuned and scanned across absorption features of various molecules in the 9–12–μm region. Its possible use as the transmitter for an infrared lidar for remote monitoring of atmospheric trace species is also to be emphasized. The narrow emission linewidth obtained in an SLM operation is compatible with both range-resolved sounding and coherent heterodyne detection. The transmitter tuning capability provides a means of probing species concentrations at various altitudes by taking advantage of the dependence of absorption linewidths on altitude in the infrared, and tuning the sounding frequency to a value which optimizes the interaction at the desired altitude. As an example, it is possible to probe a tropospheric specie, such as ozone, from a spaceborne platform by using sounding frequencies which penetrate the stratospheric ozone layer and interact with the broader ozone absorption lines at lower altitudes.

The experimental arrangement is shown in Fig. 1. The TEA CO$_2$ laser is a Lumonics 102-2 model operated at pressures around 700 Torr with a flowing mixture of He: CO$_2$: N$_2$ (85:9:6). The gain section is 1 m long and the total cavity length is 2.3 m, corresponding to a longitudinal mode spacing of 65 MHz. The optical cavity is formed from a Littrow-mounted reflection grating (150 lines/mm) and a

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