A 32-GHz REFLECTED-WAVE MASER AMPLIFIER WITH WIDE INSTANTANEOUS BANDWIDTH

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An eight-stage 32-GHz reflected-wave ruby maser has been built. The maser operates in a 3-watt closed-cycle refrigerator (CCR) at 4.5 kelvin and is capable of 21-dB net gain with an instantaneous bandwidth of 400 MHz. The input noise temperature referred to the room temperature flange is approximately 21 kelvin.

In recent years, NASA has been evaluating the relative advantages of X-band (8.4-GHz), Ka-band (32-GHz), and optical communication links for its future deep space communication needs [1]. As a result, the Deep Space Network is planning to upgrade its current capabilities by the addition of a Ka-band downlink. The 500-MHz band from 31.8 to 32.3 GHz is allocated for that purpose. An important component in achieving that goal is the development of low-noise front-end amplifiers at 32 GHz. One promising approach, drawing upon JPL's experience and success with masers, is to develop a 32-GHz ruby maser. This report describes the first such device built at this frequency by the Microwave Electronics Group at JPL. The design of this maser draws upon previous experience in building similar amplifiers at 22 GHz (K-band) [2].

A block diagram of the maser is shown in Figure 1. It consists of eight stages of ruby-filled waveguide connected in series with eighteen junction circulators. This design was chosen to achieve our goal of low noise and wide instantaneous bandwidth. Low noise is possible because of lower losses than typically achieved with a comb-type slow-wave structure. Wide instantaneous bandwidth is achieved by using a large amount of ruby (approximatley 60 cm in total length), and artificially broadening the ruby linewidth with a magnetic field gradient. The number of stages is dictated by our goal of low gain ripple, convenient magnet size, ease of fabrication of the ruby bars, and good noise performance across the band. The absence of a resonant slow-wave structure also allows for relatively wide tunability. The tuning range is limited only by the frequency response of the junction circulators. This particular maser will tune from approximately 29 to 34 GHz. However, because of the large pump power requirements to invert the large amount of ruby, we have chosen to operate with fixed tuned IMPATT oscillators, effectively making this a fixed frequency amplifier at this time.

We have continued the use of reduced height waveguide to obtain broader band circulator operation and ease the matching into the ruby-filled guide. Because of the large magnetic field required, a single superconducting racetrack coil completely enclosed in a Hiperco box is used. This magnet does not suffer from the fringing field problems associated with the open Cioffi style magnets [3] used at K-band. The ferrites in the circulators are biased simultaneously with a separate superconducting magnet. Previously, permanent magnets were used for each junction [2].

Pump power requirements are more stringent for 32-GHz operation than for the 22-GHz masers. Waveguide and structure losses are higher and the ruby is more difficult to invert due to smaller transition probabilities. More importantly, the pump power is divided eight ways instead of four ways as in the K-band case. Therefore, we are using four IMPATT oscillators purchased from Hughes Aircraft Company-Microwave Products Division. The total power output is 400 mW. The power from the IMPATTs is combined in pairs with hybrid couplers outside the vacuum vessel. The four waveguide outputs from the hybrids enter the closed-cycle refrigerator (CCR) and are split with four E-plane power splitters into eight channels. These power splitters were manufactured at JPL because they are not commercially available. The power is then carried to each ruby separately in WR-15 waveguide and impedance-matched to the ruby-filled guide. This ensures an even power distribution among all eight stages.

The ruby is single crystal and grown by the Czochralski process by Union Carbide. The chromium-to-aluminum concentration ratio is approximately 0.05%. The ruby is cut and oriented so the c-axis is 54.73 degrees to the dc magnetic field. The energy levels of the ground state of the chromium spins are shown as a function of magnetic field for this orientation in Figure 2. Population inversion is achieved by push-pull pumping the 1-3 and the 2-4 transitions [4]. The signal transition is the 2-3 transition.

The signal enters the circulator block and passes through two junctions. The junctions with the terminations on the third port prevent any reflected signal from finding its way back to the input. After passing through two circulators, the signal enters the first ruby bar. The signal travels the full length of the ruby bar, growing exponentially with distance, and is reflected at the pump inputs. It travels back up the bar, still being amplified, and is directed by three junction circulators into the second stage. The gain of each stage depends on the bandwidth, but it is typically 5 dB. The signal makes a total of 26 passes through the junction circulators.

The natural linewidth of ruby is 60 MHz. Therefore, to achieve masers with wider instantaneous bandwidths, it is common practice to inhomogenously broaden the line shape by placing different parts of the ruby in different dc magnetic fields [4]. For large bandwidths, an efficient and convenient technique is to employ a linearly staggered magnetic field along the length of the ruby. We employ a 222-gauss field gradient along the length of the rubies.

The noise temperature of a reflected-wave maser can be thought of as arising from three distinct noise sources. The first is losses in the circulator junctions and waveguides connecting the ruby channels. The second is losses in the waveguide containing the ruby and the ruby itself. The last is spontaneous emission from the ruby. There are two additional losses preceding the 4.5-kelvin input to the maser. These are losses in the feedhorn and losses in the waveguide and windows between the room-temperature flange and the maser input. The thermal isolation between the room-temperature window and the 4.5-kelvin station is achieved using two choke flanges and a cooled section of waveguide between them. One of the choke flanges is at 70 kelvin, and the other choke flange is at 4.5 kelvin. The noise contribution of the horn is estimated to be 4 kelvin. The noise contribution of the input lines is estimated to be 3 kelvin. Adding all these contributions together, we estimate the total system noise temperature with net maser gain of 40 dB, 30 dB, and 20 dB to be approximately 16 K, 18 K, and 23 K, respectively. These agree very well with the experimental results.

There are several sources of gain ripple in this maser. One source is mismatch between the circulator junctions and the rubies. Another source is cross-talk between ruby stages where the structure mates with connecting waveguide flanges. A third is uneven pumping of the rubies due to a frequency-dependent coupling of IMPATT pump power. Of these different sources of ripple, only the first is relatively easy to measure. The reduced height guide to ruby-filled guide VSWR has been measured at room temperature and is typically 1.21. The VSWR into the circulator junctions has also been measured at room temperature and is typically 1.32. Therefore, the equivalent circulator-ruby VSWR is somewhere between 1.1 and 1.6, depending on the path length between them.

The copper structure that houses the eight ruby bars is constructed in three parts like a sandwich (see Figure 3). The center section is flat on both sides and forms one broad wall of the waveguide. The remaining three walls are formed by machining grooves in the upper and lower sections of the sandwich. The dimensions of the ruby-filled guide are 0.100 inches by 0.050 inches. There are four grooves in each section. The center section also contains channels through which liquid helium flows to cool the rubies. This was an attempt to provide the optimum cooling possible in a vacuum environment. This effectively eliminated all pressed contact thermal resistance between the rubies and the helium. Although there was a gain improvement of a few dB, the improvement was not as large as had been hoped. The ruby bars are firmly pushed against this center plate by spring-loaded copper pins. The rubies are flush at the pump end of the structure. At the signal end of the structure, the rubies are tapered. To further improve the impedance match from the reduced height air-filled guide to the ruby-filled guide, quarter-wave transformers are machined into the side walls of the grooves.

The leakage of signal power from the grooves in the top section to grooves in the bottom section at both ends of the structure has been reduced by lapping the structure completely assembled (minus the rubies) with a special fixture. After lapping, the structure is never disassembled completely. The rubies are carefully inserted and removed without disassembly of the structure.

There are two separate superconducting magnets in this maser. Both magnets operate in vacuum and are cooled by thermal conduction to the liquid helium. One magnet is used to provide the 11.8-kilogauss dc field to Zeeman-split the energy levels to achieve the necessary 32-GHz frequency separation between levels 2 and 3. This magnet coil consists of 3,056 turns of NbTi (T48B) wire. The wire is purchased from Supercon Inc. of Shrewsbury, Mass. The coil windings are prevented from moving by vacuum-impregnating the coil with Scotchcast 235 epoxy, a 3M product. The second magnet is used to bias the ferrite pucks in the circulator block assembly.

The circulator block consists of 18 symmetrical Y-junction H-plane circulators. The circulators are constructed in reduced height waveguide. Each junction consists of two ferrite pucks attached to the upper and lower waveguide broad walls. The pucks are approximately 0.107 inches in diameter and 0.020 inches tall. The ferrite material used is type TT 2-111. It is commercially available from Trans-Tech, Inc. in Gaithersburg, Maryland. It is a nickel-zinc ferrite with a saturation magnetization at 4.2 K near 7000 gauss. Each junction also employs a teflon matching element. This design is basically a frequency-scaled version of a design used at K-band [2]. The circulator block is constructed similarly to the maser block (see Figure 4). It consists of a sandwich of three pieces of copper. Nine of the circulators are between the top two layers and nine are between the bottom two layers. The top and bottom row are connected in series by a length of reduced height guide.

The question of how to best pump the ruby to obtain population inversion depends to some extent on the pump power required. It is well known that ruby becomes more difficult to pump at frequencies large compared to the zero field splitting of 11.5 GHz. In order to determine the required pumping power, some experiments were carried out using a single bar of the ruby in liquid helium. We found that approximately 40 mW was required at the input to a ruby channel in order to achieve an inversion ratio (gain with pumps on/absorption with pumps off) near 1.0 over 500 MHz of signal bandwidth. After adding in the waveguide losses and window losses, we decided each stage would require at least 50 mW. Therefore, the total requirement for eight stages would be 400 mW. The coupling of the pump power to the rubies was accomplished with quarter-wave matching elements constructed of E=3 polystyrene doped with titania. Experimentally, the return loss looking into the pump end of a ruby bar with the matching element was approximately 15 dB.

A closed-cycle helium refrigerator (CCR) is used to provide a 4.5-kelvin environment for the maser. This refrigerator uses a CTI-Cryogenics Model 1020 drive unit to precool a Joule-Thomson expansion circuit. The refrigerator is capable of more than 3 watts of cooling at 4.5 kelvin. In addition, we have installed an adjustable Joule-Thomson valve that permits reduced helium flow rates. This allows us to achieve sub 4.5-kelvin temperatures by reducing the vapor pressure over the helium with a Leybold-Heraeus Model S65B vacuum pump. This can produce an additional 10 dB of gain.

The entire maser and refrigerator (minus the drive unit) assembly is contained within a cylindrical stainless steel vacuum housing approximately 12.5-inches inside diameter (Figure 5). The housing is constructed in two sections, each 15.5 inches in length. The housings are separated by a 4-inch tall aluminum spacer. A similar spacer is located between the lower stainless steel cylinder and the bottom plate of the housing. The four IMPATT diodes are mounted on a plate attached to the lower stainless cylinder. The four WR-15 pump waveguides enter the housing through the middle aluminum spacer. The bottom aluminum spacer contains the pump out port and some of the electrical connections. The remainder of the electrical connections, the Joule-Thomson valve adjusting rod, and the drive unit enter through the bottom plate.

The refrigerator and maser are both surrounded by a cylindrical copper radiation shield near 70 kelvin, and the maser is further shielded by a cylindrical copper radiation shield near 5 kelvin. The dual inputs are located at the top of the vacuum vessel. The entire maser package weighs approximately 200 pounds.

The performance of the maser with the field tapered as described earlier yielded a net gain of 21 dB and an instantaneous bandwidth of 400 MHz at 4.5 kelvin (see Figure 6). This is the maximum gain bandwidth product we have achieved. Higher gains with reduced bandwidth can be obtained by decreasing the frequency modulation bandwidth of the pumps. The amount of ruby absorption is difficult to measure with our current measurement setup. The power absorption is so large (because of the large amount of ruby) that the power level at the output of the maser is below the sensitivity of our diode detectors. However, the absorption certainly exceeds 36 dB. Therefore, the inversion ratio is less than 1.0 and probably closer to 0.7 (when operating at 21-dB net gain).

The noise temperature was measured as a function of gain using a Y-factor technique. In this case, the hot load was an ambient target placed over the horn and the cold load was the sky. The maser output was downconverted to S-band with a Honeywell mixer. Commercial S-band amplifiers, a tunable filter, and power meter enabled us to compare the maser output power when the input was looking at the hot and cold loads. The measured operating noise temperatures (including the feedhorn) were:

Net gain of 40 dB	T_{op} = 17 K $\pm$2.5 kelvin
Net gain of 30 dB	T_{op} = 20 K $\pm$2.5 kelvin
net gain of 20 dB	T_{op} = 25 K $\pm$2.5 kelvin

The error was estimated from the scatter in the measured values. Since these results were all obtained with a fixed magnetic field taper, in principle the noise temperature obtained with 40 dB of gain could also be the case with a bandwidth of 400 MHz, provided there was sufficient pump power and heating was not a problem. The gain ripple can be as low as $\pm$1 dB with fine adjustment of the magnetic field, IMPATT center frequencies, and sweep bandwidths.

This wide-bandwidth maser finds immediate application in continuum radio astronomy as well as deep space spacecraft communications. Plans are to use this maser in an experiment to search for spatial anisotropies in the cosmic background. To this end, a Dicke radiometer arrangement has been constructed. Other potential experiments include narrowing the bandpass and tracking the 4th harmonic of the Voyager or Galileo spacecraft X-band signal to study weather effects on a deep space communications link at 33.6 GHz.

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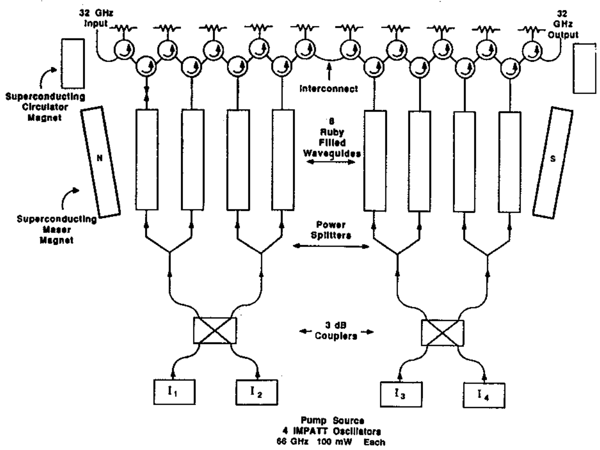

Fig. 1. 32-GHz maser block diagram

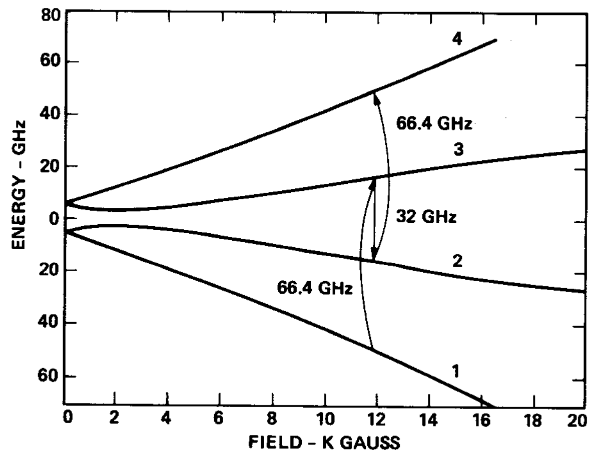

Fig. 2. Ground state energy levels of ruby with c-axis orientation of 54.73 degrees. Upward pointing arrows denote pump transitions and downward pointing arrow denotes the signal transition

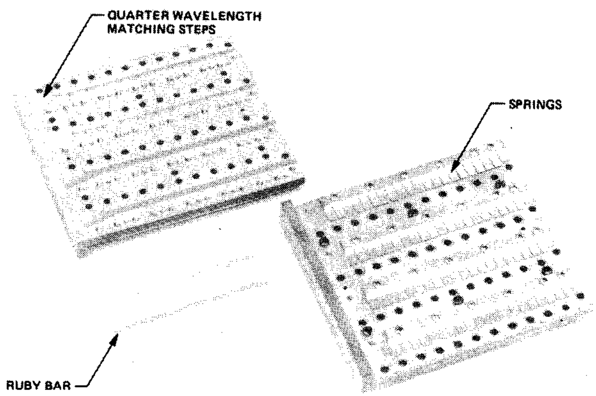

Fig. 3. Partially disassembled view of the maser structure with four of the ruby bars visible

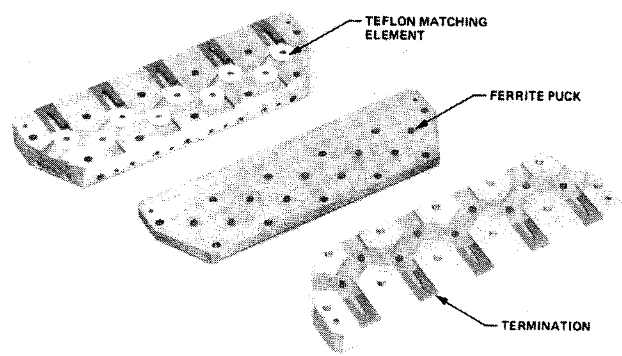

Fig. 4. Disassembled view of the circulator block showing the ferrite pucks, teflon matching elements, and terminations

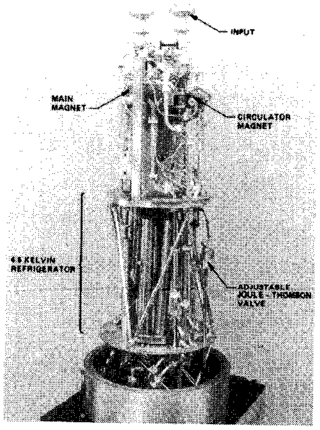

Fig. 5. Overview of the complete maser. The dual inputs of the Dicke radiometer are visible at the top. The vacuum vessel and radiation shields have been removed

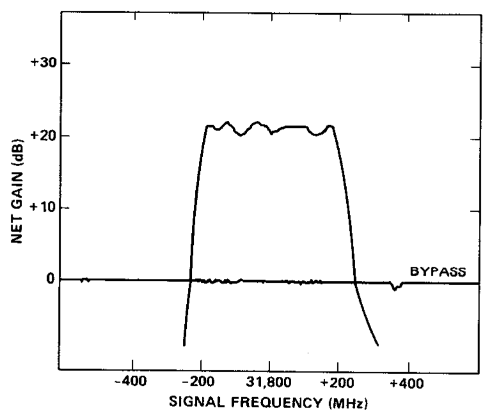

Fig. 6. Chart recording of the measured bandpass