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All Solid-State Low-Noise Receivers for 210–240 GHz

JOHN W. ARCHER

Abstract—**Low-noise all solid-state receiver systems for room temperature and cryogenic operation between 210 and 240 GHz are described. The receivers incorporate a single-ended fixed tuned Schottky barrier diode mixer, a frequency-tripled Gunn source as local oscillator and a GaAsFET IF amplifier. Single sideband receiver noise temperatures are typically 1300 K (7.39-dB noise figure) for a room temperature system and 470 K (4.18-dB noise figure) for a cryogenically cooled receiver operating at 20 K.**

I. Introduction

A NUMBER OF researchers have reported the development of heterodyne receiver systems operating at frequencies near 230 GHz [1]–[4]. However, receiver noise figures achieved have been relatively high (typically about 10 dB). Furthermore, the lack of a convenient and reliable local oscillator source with adequate output power has limited the receiver performance, and in many cases necessitated the use of relatively noisy harmonic mixers or complex dual-diode subharmonically pumped devices.

High-performance 210- to 240-GHz receiver systems have recently become practical as a result of significant improvements in single-ended mixer design [5] and the development of efficient frequency multipliers as LO sources [6]. Although receiver noise temperatures can be reduced with mixers and IF amplifiers cooled to 20 K, in many applications it is desirable that the receiver be readily portable and operate at 300 K ambient without the necessary complicated closed cycle helium refrigerators and vacuum systems required for cooled operation. The primary emphasis of this paper concerns the realization of a portable low-noise receiver for room temperature operation between 210–240 GHz. One of the prerequisites for portability was the development of practical solid-state local oscillator sources for this frequency range. Results are also presented which indicate that about a factor of three improvement in receiver noise temperature can be achieved by cooling mixer and IF amplifier to 20 K, but with a necessary increase in complexity and reduced portability.

Manuscript received February 2, 1982; revised March 18, 1982. The National Radio Astronomy Observatory is operated by Associated Universities, Incorporated, under contract with the National Science Foundation.

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II. Description of the Receiver and Components

Fig. 1 shows a photograph and block diagram of the ambient temperature receiver. The cooled system is similar except for the inclusion of a small vacuum dewar and closed cycle helium refrigerator[1] in which mixer and IF amplifier are mounted.

A lightweight compact polarizing interferometer diplexer [7] is used for LO/RF combining and filtering. The modular construction of the diplexer (each module forms an 88.9-mm sided aluminum cube) readily enables the implementation of single or dual linearly polarized receivers. The

[1] CTI Inc., Model 21.

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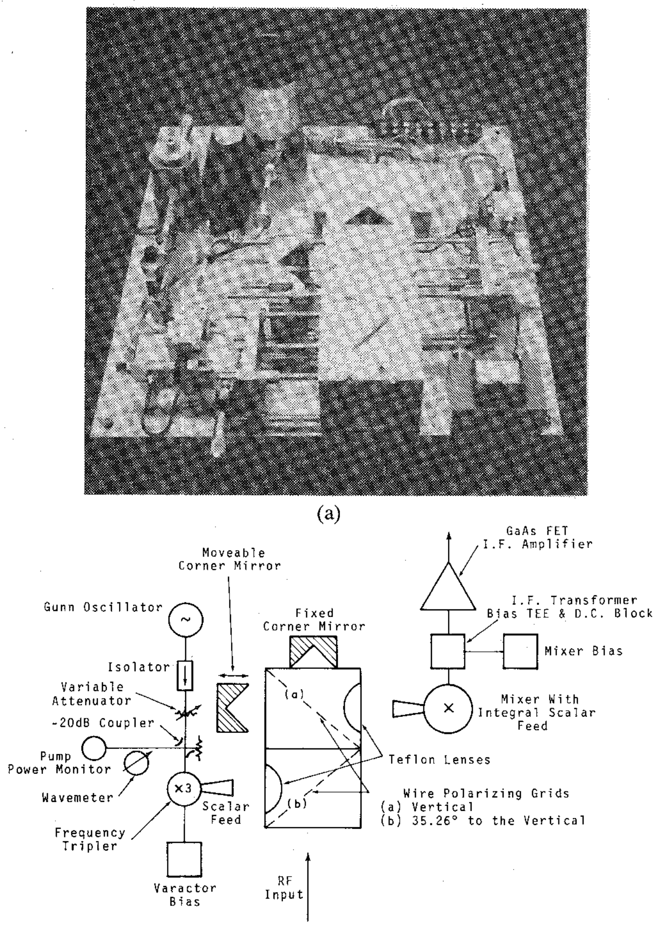

Fig. 1. (a) Photograph and (b) block diagram of the portable 210- to 240-GHz receiver designed for room temperature operation.

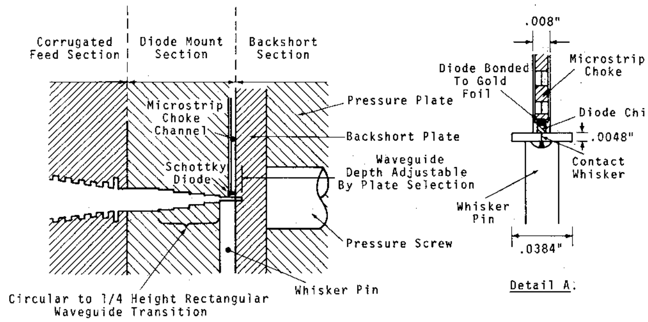

Fig. 2. A sketch of the mixer mount in partial cross-section (not to scale) shows the principal features of the design. Detail A shows the diode mounting and contacting geometry.

polarizing grids used in the diplexer are free-standing 0.05-mm diameter BeCu wire grids with 75 wires per centimeter mounted on removable circular cylindrical forms.

When adjusted for operation at any frequency between 200 and 240 GHz with a 1.5-GHz IF center frequency, the diplexer provides a theoretical -1-dB passband width for each RF sideband of the LO, of 980 MHz and measured rejection for the LO noise sidebands of greater than 20 dB. Teflon dielectric lenses are employed to match the LO and mixer scalar feed patterns to the quasi-collimated beam within the diplexer. The lenses have a focal length of 45.7 mm, a diameter of 55.9 mm, and are grooved on the surfaces to reduce reflection losses. In the cooled receiver, the lens also serves as a window at the dewar vacuum/air interface. The far field -11-dB full beamwidth of the lens corrected mixer feed pattern is 4.2°, independent of frequency between 200 and 240 GHz. The total diplexer loss, including lens reflection and feed coupling losses, is 0.40 dB over this RF frequency range when operating with a 1.5-GHz IF.

The mixer, shown schematically in Fig. 2, is a single-ended fixed tuned mount with integral scalar feed, developed from an earlier design [5]. It comprises a whisker contacted Schottky barrier diode mounted in reduced height waveguide of dimension 0.122 mm×0.978 mm. A five-section circular to rectangular waveguide step transition couples power from the feed to the reduced height waveguide. The GaAs Schottky barrier diode, fabricated by R. Mattauch at the University of Virginia (designated type 2P8-400), has a zero bias capacitance of 6.5 fF and a dc series resistance of 10 Ω at 300 K. The diode is bonded to a 0.076 mm thick crystalline quartz dielectric microstrip RF choke which is epoxied[2] in a 0.203-mm×0.203-mm channel in the diode block so that the diode is recessed into the channel, itself forming the first capacitive section of the choke. The diode mounting structure is similar to that described by Kerr *et al.*, [8] but with the orientation with respect to the waveguide described by Cong *et al.* [9]. The choke comprises a 10-section high/low impedance design with transmission line characteristic impedances of 99 Ω and 28 Ω, respectively. The lengths of the sections were optimized with the aid of a network analysis program [10] to ensure that the choke presents a reactive termination to the diode at frequencies up to at least the third harmonic of the local oscillator. The diode is contacted with a 0.0127-mm diameter phosphor bronze whisker of 0.178-mm unbent length, attached to a 0.51-mm diameter gold-plated BeCu alloy pin which is an interference fit in the mixer body. The whisker is bent so that it just spans the guide and the pin sits flush with the guide wall after contacting.

The mixer used in these receivers employs a novel fixed backshort structure for mount tuning. The backshort is implemented with the aid of a section of short circuited waveguide electroformed into a backing plate 1.760 mm thick. The backshort plate is held in place adjacent to the block containing the diode by a clamping block attached to screws which pass through the mixer body. Backshort plates with a range of diode to short spacings are available to facilitate initial mixer tuning. This method of mount tuning has distinct advantages over that used in an earlier design [5] in that it is much more mechanically stable, exhibits repeatable performance, and offers improved mixer bandwidth.

The mixer IF output is connected to an integral IF matching transformer, bias tee, and dc block which results in an IF output VSWR of less than 1.2:1 between 1.2 and

[2]Sears, Roebuck and Co., 2-part epoxy, stock number 9 8059.

1.8 GHz, when the mixer is operating at optimum LO and dc bias levels. The transformer/tee/block uses coaxial transmission line sections, as shown in Fig. 3, to achieve the desired performance. It was designed with the aid of a network analysis program employing optimization techniques [10].

Fig. 4 shows typical mixer performance as a function of LO frequency with tuning left fixed. These measurements were made with the aid of a stable, precisely calibrated 1.5-GHz IF radiometer in conjunction with the quasi-optical LO combining system described above. The results have been corrected for the signal loss associated with the diplexer, but not for residual IF mismatch and were determined by conventional techniques with 300 K and 77 K RF loads provided using Eccosorb AN-72 formed into a pyramidal shape for minimal error due to reflections from the terminations. All single sideband values quoted assume equal sideband gains and are based on double sideband measurements. The sideband gains for the mixers used here have been measured and found to be equal to within 5 percent [11].

It can be seen, for mixer 1A, with diode and tuning optimized for 300 K operation, that the SSB mixer temperature is less than 950 K between 210 and 240 GHz, reaching a minimum of 800 K at 228 GHz. Conversion loss, which includes corrugated feed horn losses, estimated to be about 0.25 dB, is less than 7.25 dB between 210 and 240 GHz with a minimum of 6.60 dB at 228 GHz. For room temperature operation, the dc bias voltage was held fixed at a typical value of 0.620 V during the measurements, and the LO power was adjusted to give a mixer current of 1.10 mA. For mixer 3, optimized for cooled operation at 20 K, the SSB cooled mixer temperature is less than 350 K with a minimum of 250 K extending from 220–230 GHz. The conversion loss response is very similar to that obtained with mixer 1A. DC bias conditions were typically 0.89 V at 0.40 mA for cooled operation.

In the receiver, the IF signal is normally fed to a low-noise GaAsFET amplifier [12]. At 300 K ambient typical amplifier noise temperature is less than 70 K between 1.2 and 1.8 GHz with a gain of 28±1 dB and an input VSWR of less than 1.4:1 over the same range. For an amplifier designed to be cooled to 20 K, the noise temperature falls to less than 15 K over this frequency band, with a small increase in gain and little change in input match compared with the room temperature version.

The local oscillator source is a frequency tripled, mechanically and electrically tuneable Gunn oscillator. The harmonic generator employs a split block crossed waveguide design [6] shown in Fig. 5. Power incident in the full height input waveguide is fed via a tuneable transition to a seven-section suspended substrate low-pass filter which passes the pump frequency with low loss, but is cutoff for higher harmonics. The low-pass filter transforms the impedance of the pumped varactor at the input frequency to a convenient value at the plane of the waveguide to stripline transition. Pump circuit impedance matching is achieved using two adjustable waveguide stubs with sliding contacting shorts. One stub acts as a backshort for the probe type waveguide to stripline transition and a second as an E-plane series stub located $\lambda_g/2$ (at the pump wavelength) towards the source from the plane of the transition. Mechanical adjustment of these tuners typically enables the input to be well matched to the diode impedance at any frequency within the operating bandwidth of the pump waveguide.

The whisker-contacted varactor chip is mounted on the

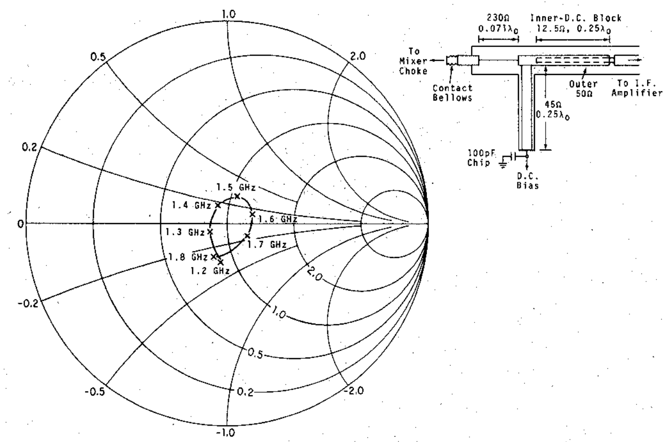

Fig. 3. Schematic and performance of the 1.2- to 1.8-GHz IF transformer, bias tee and dc block.

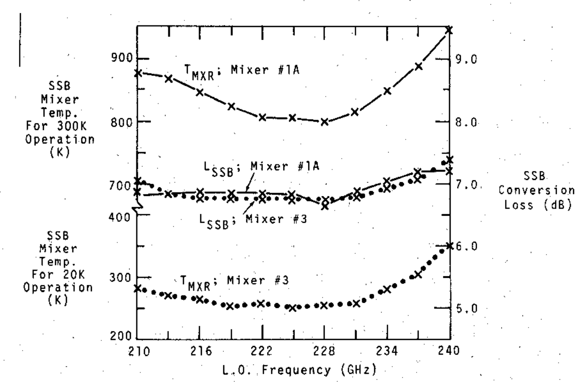

Fig. 4. Typical mixer performance for uncooled and cooled operation as a function of LO frequency. Mixer #1A was optimized for room temperature operation; mixer #3 was optimized for cooled operation.

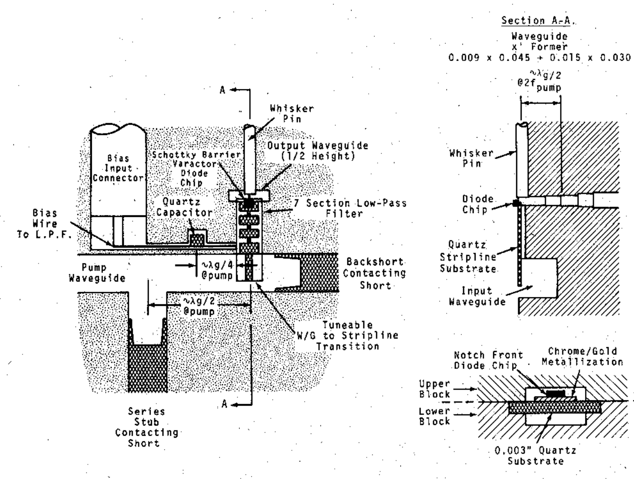

Fig. 5. A sketch of the frequency tripler in partial section (not to scale) shows the principal features of the design.

filter substrate in the reduced height output waveguide. Output tuning is accomplished with the aid of an adjustable backshort in this guide. DC bias is brought to the device via a transmission line bias filter. The bias circuit comprises a 140-Ω transmission line, consisting of a 0.025-mm diameter gold wire center conductor bonded at one end to a low impedance section of the low-pass filter and at the other end to a 100-fF quartz dielectric bypass capacitor and enclosed in a rectangular shield machined into the mount. The bias line approximates, at the chosen mount center frequency, a quarter-wave short-circuited stub.

A quarter-wave three-section impedance transformer couples the reduced height guide to the full height output guide. Power can flow in the reduced height guide at the second harmonic whereas the output guide is cut off at this frequency. The transformer is thus used to implement a second harmonic idler termination by spacing it approximately $\lambda_g/2$ (at the second harmonic wavelength) from the plane of the diode.

The varactor diode is a Schottky barrier device fabricated by R. Mattauch at the University of Virginia (designated 5M2) with a zero bias capacitance of 21 fF and a dc series resistance of 8.5 Ω. The breakdown voltage is 14 V at 1 μA. These devices have a highly nonlinear capacitance versus voltage law which approximates the inverse half-power behavior of the ideal abrupt junction varactor to within about 2 V of the breakdown limit.

The frequency tripler exhibits typical conversion efficiency greater than 3 percent for output frequencies between 210 and 240 GHz, with 50-mW pump power, when dc bias and tuning are optimized at each operating frequency. Peak conversion efficiency of 6 percent is attained at an output frequency of 222 GHz.

The 70- to 80-GHz Gunn oscillator employs a commercial GaAs Gunn diode[3] in a quarter-wave radial line resonator structure, as shown in Fig. 6. The 2.667-mm diameter resonator is mounted in a waveguide with nonstandard dimensions, which were adjusted to optimize the coupling between resonator and guide in the 70–80-GHz range (3.81 mm × 1.55 mm). A taper transformer couples this waveguide to the standard WR-12 output guide (3.10 mm × 1.55 mm). DC bias and ground return are brought to the diode via multisection coaxial choke structures made from tellurium copper. The choke center conductors are coated[4] with a spray-on fluorocarbon material to insulate them from the outer wall. The bias and heatsink assembly is designed so that the vertical position of the diode in the guide may be continuously varied by approximately ±0.125 mm with dc bias applied to the device.

The operating frequency of the oscillator is primarily determined by the resonant frequency of the radial line/Gunn diode combination. A contacting backshort is used to optimize the coupling between resonator and guide at each operating frequency, but the adjustment of this short has only a second order effect on oscillator frequency. Varying the spacing between the guide wall and the radial hat changes the fringing field strength at the edges of the resonator and alters the fringing capacitance. Hence, it is possible to tune the oscillator by varying the vertical position of the hat in the guide [13]. For the present design, a reduction in height from about 1.25 mm–1.00 mm corresponds to a frequency change from 80–70 GHz.

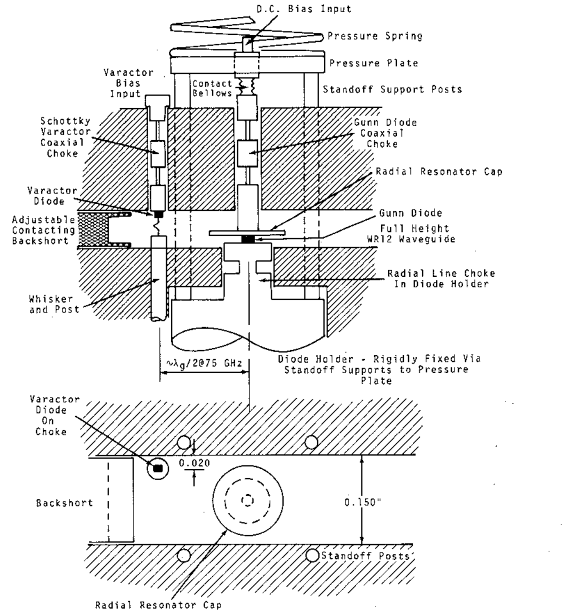

Fig. 6. A sketch of the Gunn oscillator mount in partial section (not to scale) shows the principal features of the design.

Since the backshort adjustment has a small but measurable effect on operating frequency (for approximately 1-dB reduction in output power, the frequency can be pulled on the order of 100 MHz), it has been found possible to provide limited electrical tuning of the oscillator with a varactor diode mounted about $\lambda g/2$ from the Gunn diode plane, in the backshort guide. The diode, a Schottky barrier, whisker-contacted device similar to those used in the frequency tripler, is mounted on a coaxial choke in a position offset from the guide axis. The degree of offset, which determines the coupling between guide and varactor circuit, has been experimentally optimized to give an electrical tuning range of about ±50 MHz at any operating frequency with less than 1.5-dB change in output power. The electrical tuneability of the oscillator should allow it to be phase locked, although this has not yet been attempted.

Oscillator performance is illustrated in Fig. 7. Output power varies between a minimum of 45 mW and a maximum of 55 mW as the oscillator is tuned over the range 70–80 GHz. DC bias requirements are approximately 5 V at 1.2 A. As is also shown in Fig. 7, the Gunn oscillator/tripler combination can provide a minimum of 2.0 mW at any frequency between 210 and 240 GHz.

III. Receiver Parameters and Performance

The complete room temperature receiver package occupies a volume of less than 0.015 m^3 and weighs less than 9.0 kg (excluding power supplies). Typical mixers and

[3]Hughes Aircraft Company, Model 47205H-0305.

[4]Whitford Corp., Xylan 1000 Fluorocarbon Coating.

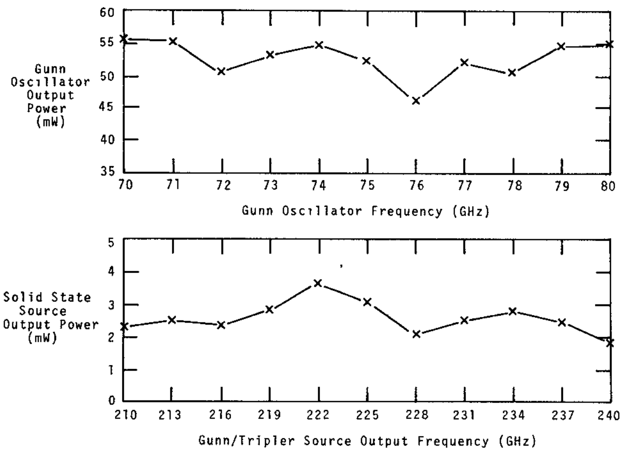

Fig. 7. Solid state source output power as a function of frequency.

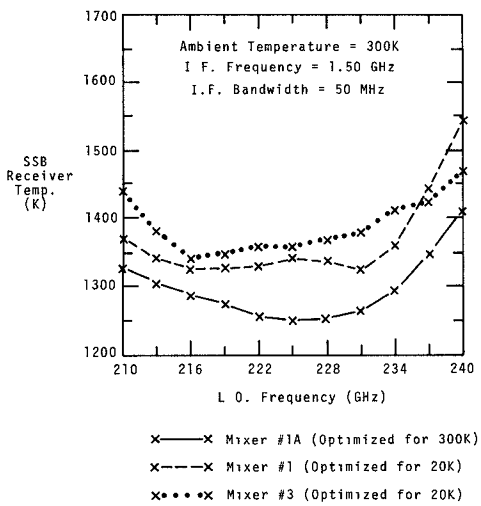

Fig. 8. Receiver performance at 300 K ambient as a function of LO frequency, for three different mixers. Mixer #1A was optimized for 300 K operation; mixers #1 and #3 for operation at 20 K.

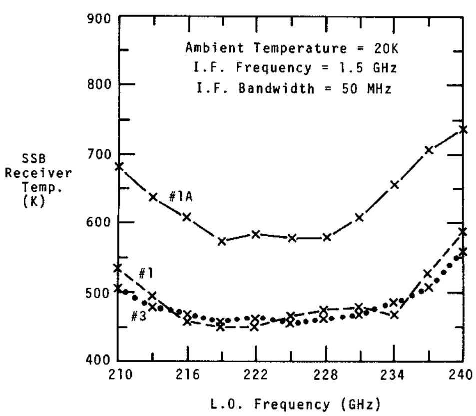

Fig. 9. Receiver performance at 20 K ambient as a function of LO frequency, for three different mixers.

frequency multipliers used in the receiver have undergone extensive mechanical shock and vibration testing to evaluate their performance under extreme environmental conditions. They can withstand for an indefinite period, continuous vibration with a sinusoidal acceleration of up to 4-G peak at 60 cycles per minute rate. However, permanent

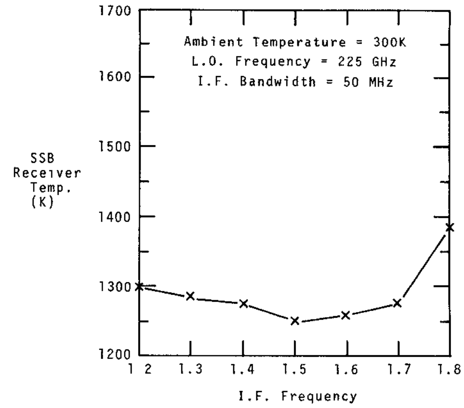

Fig. 10. Receiver performance as a function of IF center frequency for mixer #1A at 300 K.

changes in diode $I-V$ characteristics are observed after five minutes at 10-G peak at the same repetition rate. The mixers have also been tested under thermal shock conditions. A typical mixer can withstand a minimum of five sequential immersions in liquid nitrogen, each followed by warming to room temperature in an evacuated desiccator, without detectable change in performance.

Receiver RF performance was determined using similar techniques to those used in evaluating mixer behavior. As the LO frequency was varied between 210 and 240 GHz and the diplexer tuning adjusted accordingly, the performance curves shown in Figs. 8 and 9 were obtained at 300 K and 20 K ambient, respectively, for three different mixers. For the room temperature receiver, the single sideband receiver noise temperature with mixer 1A varies between 1400 K at the band edges to a minimum of 1250 K at band center. The IF center frequency for these measurements was 1.5 GHz with a bandwidth of 50 MHz. Typical LO power required was less than 1.5 mW at the tripler output.

When the mixer and IF amplifier are cooled to 20 K, the SSB receiver temperature varies between 575 K at the band edges and a minimum of 470 K at band center (mixers 1 and 3). The IF center frequency and bandwidth remain the same for these measurements. The required LO power drops to about 300 μW at the tripler output.

For a fixed LO frequency of 225 GHz, the instantaneous response shown in Fig. 10, as a function of IF frequency, was measured for the 300 K receiver. The usable instantaneous bandwidth is at least 500 MHz with less than 100 K degradation in receiver noise temperature relative to the value at 1.5 GHz.

IV. Conclusion

The results described in this paper demonstrate the feasibility of building all solid-state high performance receiver systems to utilize the 200- to 300-GHz atmospheric transmission window. It has been shown that portable, mechanically robust receivers, which exhibit SSB noise temperatures of the order of 1300 K, can be built for room temperature operation. Cooling the mixer and IF amplifier to 20 K results in about a factor of three reduction in receiver noise temperature, but with necessary penalties of increased weight and complexity and limited portability. Current research is aimed at developing components that would enable all solid-state low-noise receivers to be constructed for operation at frequencies up to 350 GHz.

Acknowledgment

The author wishes to thank N. Horner, who assembled the mixers and multipliers, G. Taylor, who fabricated the diplexer, Dr. S. Weinreb and R. Harris, for supplying the GaAsFET amplifiers, and Dr. R. Mattauch for providing the Schottky barrier diodes.

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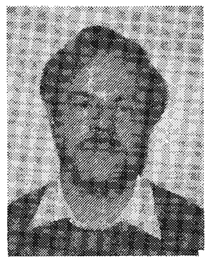

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Short Papers

A New Design for 1-CM Rutile Traveling Wave Masers

JAN ASKNE, MEMBER, IEEE, S. GALT, AND E. KOLLBERG

***Abstract*—A new design of a rutile traveling wave maser is described. A dielectric rod waveguide is used as the interaction circuit. Essential mode coupling problems have been worked out in order to make the maser work properly. The advantage with this type of maser is the simplicity in the manufacturing and the very low insertion loss. A maser designed for the frequency range 26–29 GHz has been built, tested, and used in radio astronomical observations.**

Manuscript received February 11, 1982; revised March 29, 1982. This work was supported in part by the Swedish Board for Technical Development.

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I. Introduction

For *K*-band (18–26 GHz) and *Ka*-band (26–40 GHz) frequencies several maser designs have been described (e.g., [1], [2], [3]), and as far as low noise is concerned, no other device can yet compete with the maser in this frequency range. A flange noise temperature of about 15 K has been reported for a 500-MHz-wide *K*-band maser [1] and about 35 K for a 75-MHz-wide *Ka*-band maser [3]. The noise temperature in both cases is limited by the noise contribution of the input waveguide rather than the amplifier itself.

The present paper describes a maser design which can be

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