of 80 km/h, a communication area length of 2 m, antenna gain of 15 dB and a gate height of 5 m. As another example, a signal-to-noise ratio of 35 dB with a signal bandwidth of 1 MHz can be obtained at a distance of 100 m with an antenna of 20 dB gain.

Conclusion

The new configuration can make a transceiver very compact. The used packaged millimeter-wave diode and the minimal component count would contribute to the increase of reliability. Adjustment is easily made to balance the MM. This type of transceiver can be used for a variety of millimeter-wave systems for civilian use.

Acknowledgment

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A *V*-Band Communication Transmitter and Receiver System Using Dielectric Waveguide Integrated Circuits

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***Abstract*—A *V*-band communication transmitter and receiver is described. Both units make extensive use of passive microwave components fabricated using millimeter-wave insular line integrated circuits (MILIC's). These components consist of rectangular dielectric rod antennas, a MILIC ferrite isolator, a bandpass ring filter, a directional coupler, and sections of dielectric insular waveguide. The passive insular waveguide components are integrated together, along with split block metal waveguide mounts for the active devices, in order to form the RF circuitry of the transmitter and receiver.**

I. Introduction

THIS PAPER describes a short-range one-way *V*-band communication system. The system consists of a separate transmitter and receiver module complete with all oscillator, mixer, modulation, biasing, and IF circuitry necessary for its operation. Millimeter-wave insular line integrated circuits (MILIC's) [1], [2] were extensively used for the passive microwave components in the RF sections of each unit.

The transmitter and receiver modules, which will be described, are the end product of a developmental effort of dielectric insular waveguide and associated components [3], [4]. The projected advantages of the MILIC's include: low production costs, high reliability, compact size, and applicability to system work in the *V* band and above. The dielectric insular line components which were developed and integrated together to form the complete system include: rectangular dielectric rod antennas, a MILIC ferrite isolator, a bandpass ring filter, a mode transition, and a directional coupler. In addition, an IMPATT oscillator, a Gunn oscillator, and a mixer were developed in standard waveguide and integrated with the MILIC components, using appropriate transitions.

II. Transmitter Module Layout

The transmitter module consists of a series of insular dielectric waveguide components and rectangular metal waveguide devices integrated together to form a complete package. The major RF components of the transmitter are: 1) a dielectric rod antenna, 2) a MILIC ferrite isolator,

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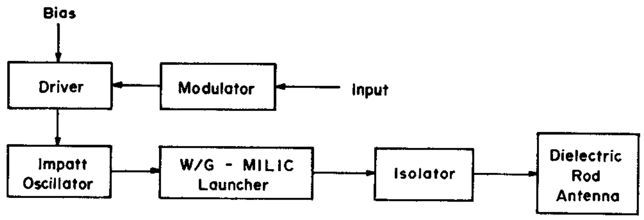


Fig. 1. Block diagram of transmitter.

3) a mode launcher from TE_{10} in metal guide to $E_{11}{}^y$ in insular guide, and 4) an IMPATT oscillator. The block diagram of the transmitter is given in Fig. 1, and the RF portion of the transmitter module is shown in Fig. 2.

A. Dielectric Rod Antenna

The dielectric rod antenna consists of a 0.040-in × 0.040-in alumina rod which has been tapered along its length. The detailed design considerations are given by Shiau [5]. The measured gain of the antenna was found to be 15.1 dB at the system operating frequency. Since the dielectric antenna protrudes out of the transmitter case, a protective polystyrene radome has been provided in order to prevent breakage. The addition of a single radome adds approximately a 0.2-dB loss to the overall system.

The dielectric antenna was designed and fabricated to be an easily replaceable component of the transmitter module. The antenna is bonded to a T-shaped fixture which is fastened to the main plate with two screws. The insular waveguide on the antenna fixture and main plate are butted together to form a continuous energy path. The effects of introducing transverse gaps in the dielectric waveguide can be found in [3].

B. MILIC Ferrite Isolator

One of the significant achievements of this effort was the development of a ferrite isolator compatible with the MILIC technology. Due to electrical, mechanical, and biasing constraints, the MILIC configuration cannot suitably adopt to the conventional ferrite devices such as the Faraday rotation isolator, the FM resonance isolator, etc. Therefore, a MILIC ferrite device was developed using a different approach. The device was developed by Nanda and can be called a "fringefield isolator" because it uses the transverse fields extending out of the dielectric region for its operation. A detailed discussion is presented in [4] and [6].

The development of a MILIC ferrite isolator required that the layout of the device and the size of the constituent parts be compatible with the MILIC geometry and technology. A cross-sectional drawing of the isolator structure is given in Fig. 3. The main line of the isolator is a composite dielectric/ferrite section, above which one bias magnet is mounted on a plexiglass frame, and below which, in the nonferrous ground plane, the other bias magnet is located.

When magnetically biased, the composite dielectric/ferrite section provides for the necessary nonreciprocal propagation through the device. For one direction of propagation, the biased ferrite causes the transverse fields to shift into the region of the film resistor, causing a high insertion loss. In the opposite direction, the fields are shifted away from the film resistor, decreasing the insertion loss. Thus the device uses the shifted fringe fields in conjunction with the film resistor to provide the optimal isolator action. The design of the isolator requires the knowledge of several parameters such as the type of ferrite material, the size of the dielectric guide, the filling factor of the ferrite slab, the strength of biasing magnetic field, and the position of the load. The determination of these parameters was done analytically and partially empirically [4], [6].

The design concept was verified by fabricating and testing two MILIC isolators. The first unit was designed for operation in the *Ku* band, and the second was the *V*-band model intended for inclusion in the transmitter module. The ferrite material used for both devices was Trans-Tech TT2-111 nickel zinc ferrite. The *Ku*-band isolator had a center frequency of 14.5 GHz, an isolation of 17.5 dB, an insertion loss of 1.8 dB, and a bandwidth of 5 percent between 10-dB isolation points. The *V*-band unit center frequency was 61.1 GHz, with an isolation of 11 dB, an insertion loss of 1.0 dB, and a bandwidth of 250 MHz between 8-dB points.

C. Mode Launcher

A mode transition was used between the transmitter oscillator and the dielectric insular guide feeding the MILIC isolator. This type of launcher consists of three basic sections. The first of these sections is where the dielectric waveguide enters the launcher. In this section, the cross section of the dielectric guide does not change, but there is a 4.6° *E*-plane linear taper in the metal waveguide down to the height of the dielectric waveguide. The second transition section consists of a rectangular metal waveguide of the same height as the dielectric line, it is here that the dielectric waveguide is tapered to a point in the *H* plane. The third section consists of a linear *E*-plane taper in the metal waveguide back to the desired terminating waveguide height. The height of terminating waveguide is that of the transmitter oscillator, i.e., 0.074 in.

D. IMPATT Oscillator

The transmitter oscillator is a 100-mW IMPATT diode oscillator, Model 4415-H (Hughes Electron Dynamics Division, Torrance, CA). The transmitter modulation and driver circuitry are located on a PC board mounted above the mode transition. The external dc bias and signal input are provided through input jacks located at the rear of the transmitter package.

The transmitter circuitry consists of a current regulator for the IMPATT oscillator diode, and a resistor network to convert the modulation input voltage to a variable current which frequency modulates the oscillator. A separate 115 VAC power supply is provided to power the transmitter. The transmitter circuitry is shown schematically in Fig. 4.

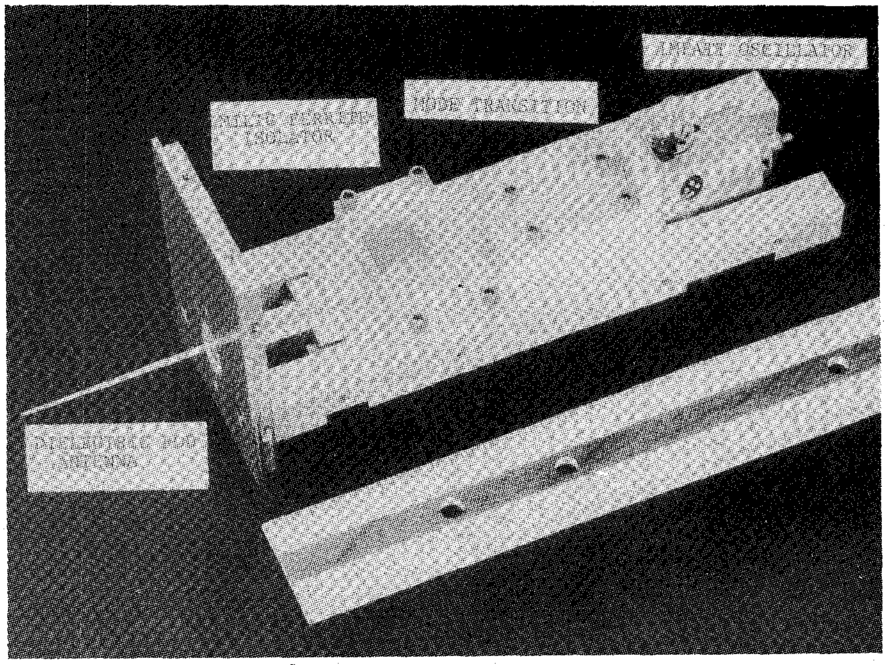


Fig. 2. Transmitter module RF circuitry.

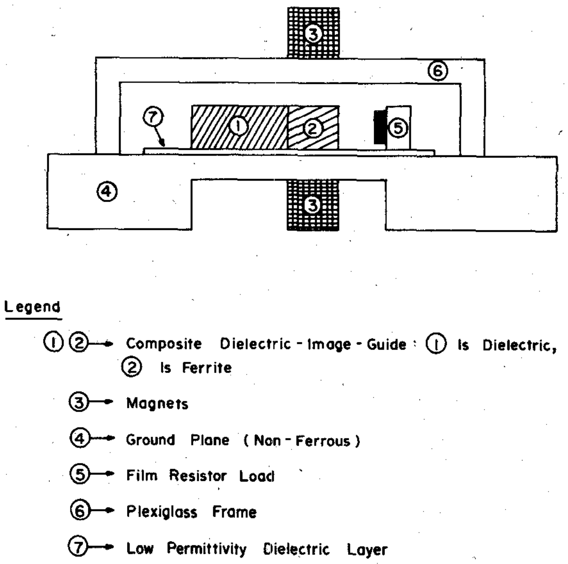


Fig. 3. MILIC ferrite isolator—typical layout.

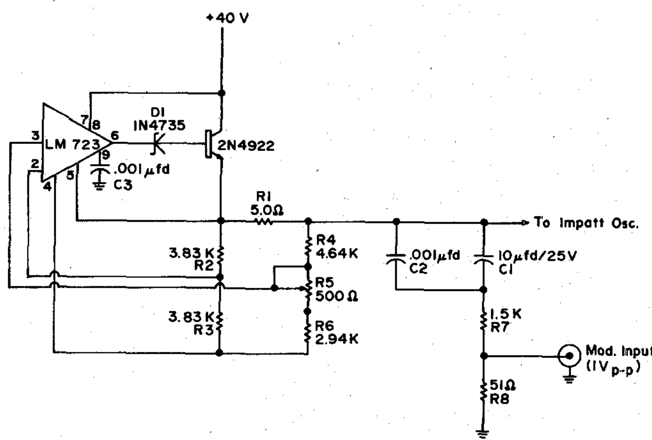


Fig. 4. Schematic of the transmitter current regulator and modulation circuitry.

The IMPATT oscillator requires a regulated current in the range of 200 to 400 mA at a voltage of approximately 22 V. A μA723 integrated circuit with an MJE521 current-boost transistor is employed in the regulator. The output current is sensed as the voltage drop across the 5.0-Ω resistor R1.

The oscillator current is adjusted by means of R5, although the range of this adjustment is purposely limited in order to provide a more accurate current setting. If the range is not large enough to include requirement of all oscillator diodes, it may be changed by selecting other values for R4 and R6. The total resistance of R4 and R6 should be kept as close to 7.5 kΩ as possible, in order to minimize the drift of the output current with temperature.

Frequency modulation is applied to the oscillator by means of R7, R8, C1, and C2. A 1-V peak-to-peak modulating signal is applied to the modulation input and is terminated by R8. R7 appears as a constant current source to the low impedance of the oscillator and provides a small variation in oscillator current as a function of the modulation input signal. Capacitors C1 and C2 are employed to block dc and will pass frequencies down to approximately 7 Hz. The value of R7 is selected to give approximately a 10-MHz peak-to-peak deviation with a 1-V peak-to-peak input signal. This value may have to be changed if the oscillator diode is replaced, since the modulation sensitivity varies somewhat among diodes.

The power unit for the transmitter must supply approximately 12 V plus the IMPATT diode voltage, or, approximately, 35 V at a maximum of 400 mA. A full wave bridge rectifier circuit is employed with a two-section capacitor filter and an adjustable resistor to set the output voltage.

A bleeder resistor and a zener diode are included in the power unit as a measure of protection for the oscillator diode in case the cord connecting the transmitter to the power unit is accidently disconnected and reconnected with the power on.

III. Transmitter Module Evaluation

The various components of the transmitter were arranged and tested. The IMPATT oscillator was found to have an output power of about 150 mW at 61.1 GHz. Provision exists for both mechanical and electrical tuning of the oscillator. The oscillator could be mechanically tuned from 60.6 to 61.8 GHz at 298 mA and a 24.9-V bias. The current tuning was typically from 61.05 to 61.25 GHz for a current variation of 295 to 308 mA, respectively, and a fixed tuning short position.

Using an 18-dB standard gain horn as a reference, the effective gain of the transmitter chain of components was measured. At the operating frequency of 61.1 GHz, this gain was measured to be 9 dB. As already reported, the dielectric rod antenna had a gain of about 15 dB; thus the components between the waveguide launcher input and the dielectric rod antenna input had an insertion loss of 6 dB. In addition, the VSWR of the waveguide to the MILIC launcher with all of the components attached was 1.54:1 at 61.1 GHz.

IV. Receiver Module Layout

The receiver module consists of the following MILIC and standard waveguide components: 1) a dielectric rod antenna, 2) a bandpass ring-type preselector filter, 3) a hybrid 3-dB insular guide coupler, 4) a Gunn diode local oscillator, and 5) a balanced Schottky-barrier diode mixer. The package also includes the associated IF and automatic frequency control (AFC) circuitry. The receiver is intended to be operated at a frequency of 61.1 GHz with a 160-MHz IF. A block diagram of the receiver is given in Fig. 5. The actual receiver module is shown in Fig. 6.

A. Dielectric Rod Antenna

The dielectric rod antenna is the same type used in the transmitter with a 15.1-dB gain. The receiver antenna is also replaceable in case of damage, and is protected by a polystyrene radome.

B. Bandpass Ring Filter

A bandpass filter can be constructed in rectangular dielectric image or insular guide using a dielectric ring of rectangular cross section which is proximity coupled to two straight sections of dielectric waveguide. These straight sections of guide in turn form the input and output lines of the four-port device. The ring is a multiple resonant bandpass device which will provide a maximum transfer of energy from one line to the other at center frequencies where the mean circumference of the ring is approximately $n\lambda_g$ ($n = 1,2,3,\cdots$). The basic analytical description of the bandpass ring filter follows the procedure given in [7], but is implemented in terms of image or insular dielectric waveguide instead of stripline [4].

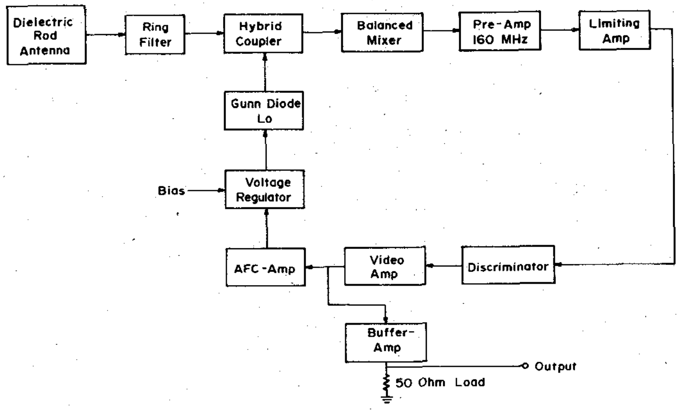


Fig. 5. Block diagram of receiver.

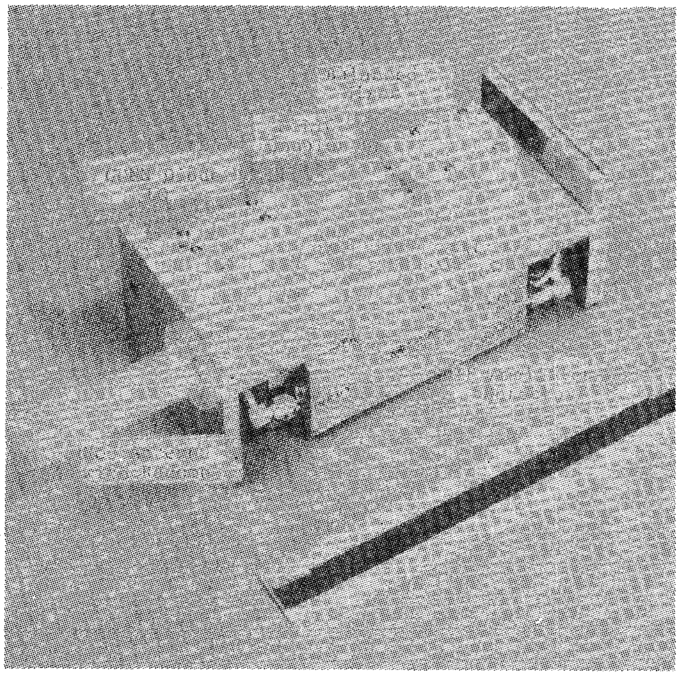


Fig. 6. Receiver module.

A preselector MILIC ring filter was provided on the input line of the receiver for image rejection. This ring filter has a bandpass frequency response centered at the system operating frequency of 61.1 GHz, which determined the passband for the receiver. The system uses a fixed frequency ring filter. It is possible to provide tuning of this input filter as described in [8].

A relative measurement of the response of the ring filter in the actual system setup was made by transmitting a swept signal into the receiver input. This was accomplished by means of a rectangular metal waveguide to the MILIC transition in place of the dielectric antenna mount. The filter output was then coupled into a detector off the line which feeds the balanced mixer. The filter response is shown in Fig. 7.

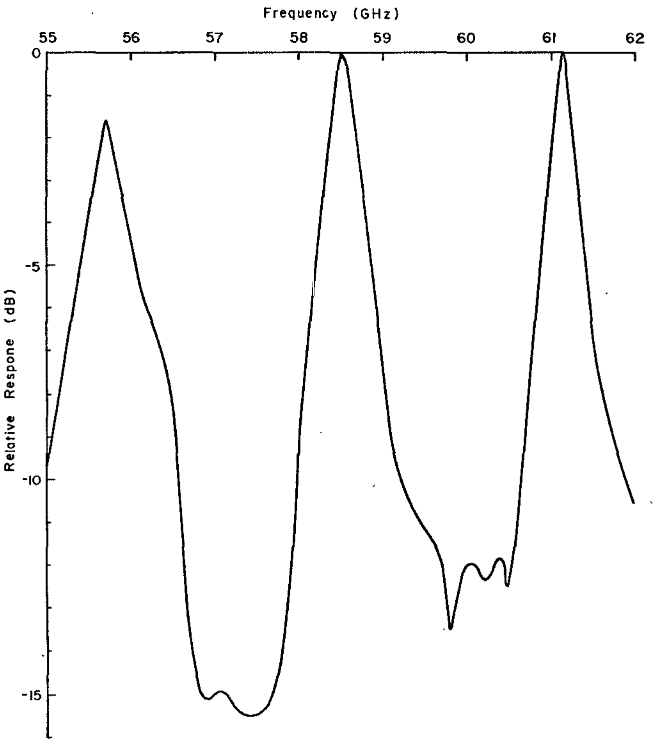


Fig. 7. Ring filter response.

C. Balanced Mixer

The signal and LO power is split by means of a 3-dB MILIC hybrid coupler and fed into a balanced waveguide mixer. The mixer uses two matched Schottky-barrier diodes (Texas Instruments' MDX-62S GaAs Schottky-barrier barrier mixer diodes). The mixer diodes are situated in a split block rectangular metal waveguide diode mount (Fig. 6). The insular waveguide feeds into a transition at the input of the mixer mount.

The insular waveguide input lines are tapered into the mount for impedance matching purposes. Behind the diodes are high-impedance stubs which are also used for matching. The top diode contact is seated in the top portion of the mount which provides an RF ground; the bottom portion is seated in a RF choke assembly. The choke assembly is a coaxial transmission line whose characteristic impedance alternates high and low approximately every quarter wavelength at the RF signal and local oscillator frequency. The resulting structure presents a very low RF impedance at the base of the diode at the RF and LO frequencies. A bellows spring located at the bottom of the choke assembly provides spring tension so that good electrical contact is made at the bottom contact of the diode. The output of each mount is symmetrically connected to a common connector. The two mixer diodes are isolated dc-wise, and provisions have been made to monitor the mixer currents.

D. Gunn Diode Local Oscillator

A Gunn diode local oscillator was used in the receiver rather than an IMPATT source in order to improve the noise figure of the unit. The Gunn diode (Microwave Associates' MA-49000) used is only rated by the manufacturer up to 50 GHz, and has only recently become commercially available. However, we have successfully operated it in the 60-GHz region.

The Gunn diode local oscillator is a split block rectangular metal waveguide mount. The diode is post mounted in a reduced-height waveguide. The adjustable short behind the diode determines the operating frequency. Bias voltage for the diode is provided through the low-pass capacitive filter. RF choking in the bias circuit is provided by a radial trap filter which puts a RF high impedance in series with the bias circuit. As an additional precaution against spurious oscillation, a tapered section of lossy ferrite material and a low-pass capacitive choke filter are used to isolate the dc circuit from the RF portion.

With the local oscillator circuit, two tuning techniques are employed. Coarse frequency tuning is provided by the short circuit located behind the diode. This has provided 2 GHz of tuning (59–61 GHz). The second method employs variation of the bias voltage. This method has provided a few hundred megahertz of frequency tuning at a sensitivity of about 200 MHz.

The output power of the Gunn diode oscillator was 25 mW at 10 GHz. This has been found sufficient to drive the balanced mixer diodes.

E. Miscellaneous Components

Thin-film attenuators are used in the receiver module as terminations and pads, where necessary. Two terminations were used on the input/output lines of the ring filter, and the local oscillator was padded in order to lessen the load dependence of the oscillator. The material which is used for this purpose is a 0.0002-in thick mylar resistive film 377 Ω/sq produced by Solitron Microwave. The pad on the local oscillator had an attenuation of about 3 dB.

F. IF Amplifier/Discriminator

In addition to the millimeter-wave portion, the receiver includes an IF preamplifier, a main IF amplifier limiter discriminator, a regulator for the Gunn local oscillator diode, AFC circuitry, and a video output amplifier. A block diagram of the overall receiver is given in Fig. 5.

Both IF amplifiers are hybrid thin-film units manufactured by LEL/Varian. The preamplifier is a model ICP-1-160-40-50 S (100-12). It has a low noise input stage that is especially matched to the impedance of the balanced mixer diodes, and has a gain of 25 dB with a noise figure of 3.5 dB. This preamplifier sets the overall receiver bandwidth, which is nominally 40 MHz (the actual noise figure was 3 dB and the bandwidth was 43 MHz). The center frequency is 160 MHz.

The main IF amplifier is a model ICF-2-160-60-50M and includes a limiter, a discriminator, and a video amplifier. When used in combination with the preamplifier, signals above −82 dBm are into limiting. The output sensitivity is 0.125 V/MHz, producing an output voltage of 1.25 V peak to peak with a 10-MHz peak-to-peak deviation. The

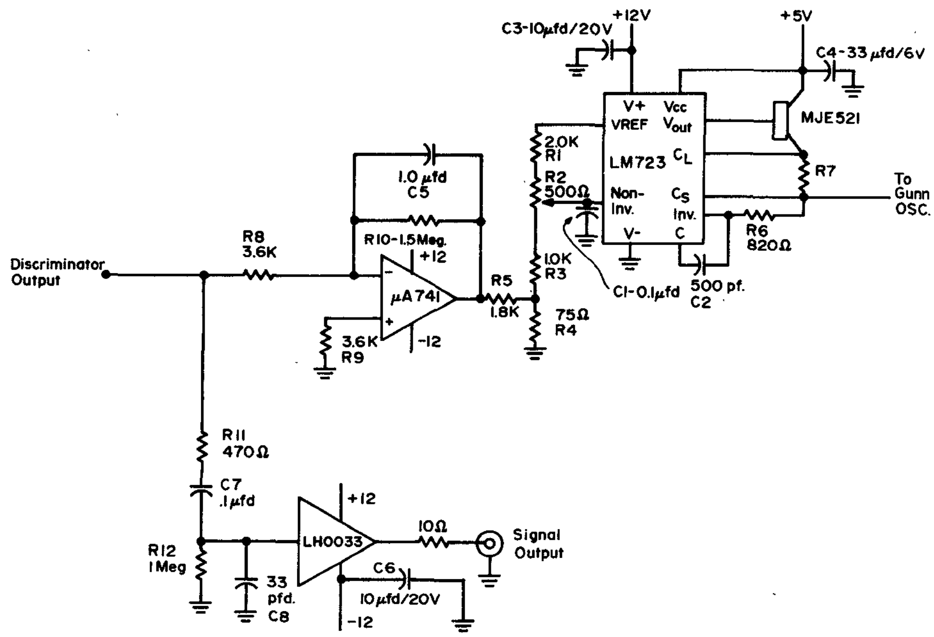


Fig. 8. Schematic of the receiver AFC and video circuitry.

discriminator linearity is better than 5 percent over the central 20-MHz portion of the passband.

A printed circuit board contains all the other receiver circuitry and is shown schematically in Fig. 8. A μA723 integrated circuit with an MJE521 current-boost transistor is employed to regulate the Gunn diode voltage. R2 allows adjustment of this voltage between approximately 2 and 3 V. A portion of the regulator requires a 12-V supply, but the actual diode current is derived from a separate 5-V supply in order to minimize power dissipation in the regulator. Maximum current is limited to approximately 1.75 A by tailoring on the length of R7, which is a short piece of resistance wire.

The AFC circuit consists of a μA741 operational amplifier, used as an integrator, and a resistor network, R4 and R5, used to introduce the AFC correction voltage into the regulator for the Gunn diode. The circuit is designed so that when the operational amplifier output voltage swings over its maximum range of nearly $\pm$12-V supply, the oscillator frequency will change by approximately 100 MHz. This limits the AFC range to that over which the Gunn diode can operate properly, The μA741 output voltage should remain near zero when both the LO and transmitter are on the correct frequency. The integrator time constant determines the lower frequency limit of the video passband; below approximately 18 Hz, the AFC circuit will degenerate frequency modulation on the input signal as well as the oscillator drift.

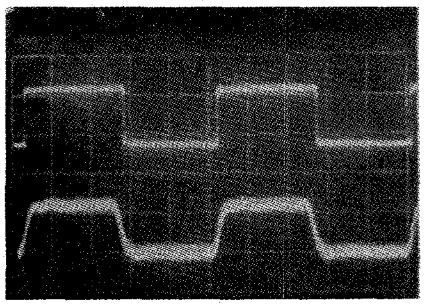
A LH0033 integrated circuit is employed as a buffer amplifier to allow a 50-Ω line to be driven by the receiver. This has nearly unit gain and supplies an output signal of approximately 1.0 V peak to peak. An *RC* network at the input of the LH0033 limits the high end of the video band to approximately 10 MHz.

A separate 115 VAC power unit is supplied for use with the receiver. It consists of two separate rectifiers, one to supply the low-voltage high current for the Gunn diode and the other to supply the plus and minus 12 V for the IF and other circuitry. The 12-V supplies use integrated-circuit fixed-voltage regulators 78M12 and 79M12, while the Gunn diode supply is regulated within the receiver.

V. Receiver Module Evaluation

Noise-figure and conversion-loss measurements were made from the receiver input, which had a standard waveguide transition, in place of the dielectric rod antennas, to the IF preamplifier output. The gain of this preamplifier (25 dB) has been subtracted from the measured values. The noise figure is based upon a comparison of the CW signal power to the noise power in a known bandwidth. The more conventional noise-figure measurement technique of using a noise source was not employed because a gas-tube source for this frequency range was not available. The bandwidth of the IF preamplifier, which determines the actual receiver bandwidth, as well as the preamplifier noise figure were verified with CW and noise-source measurements at 160 MHz. Care was taken to calibrate the *V*-band bolometer at the operating frequency with a *V*-band calorimeter unit. This ensured an accurate determination of the input signal power to the receiver.

Averaging a number of receiver loss and noise-figure measurements indicates as final values a 12-dB loss and an 18-dB noise figure. Variations among individual measurements of no more than $\pm$0.5 dB were noted. Based upon previous measurements of individual components, it is estimated that the 12-dB loss consists of a 5-dB conversion loss in the mixer itself, and a 7-dB loss in the other front end circuitry which includes the input transition, the ring filter, the 3-dB hybrid coupler, and the various butted alumina joints.



Transmitter Modulation

Receiver Output

Transmitter input power	0 dBm
Range	135 ft
Modulation signal	1 MHz square wave
Deviation	±5 MHz

Fig. 9. System input and output waveforms.

Thus the noise figure directly at the mixer input is 11 dB, including the IF preamplifier noise figure of 3.5 dB and a LO noise contribution of 1–2 dB. If these two excess noise sources are eliminated in the calculations, the noise figure of the mixer alone is 6 dB. This is 1 dB more than the estimated conversion loss.

VI. System Evaluation

Overall system performance was measured indoors in a large vacant room over a path length of 135 ft. Measurements indicate that a 0-dBm power level into the transmitter provides full limiting in the receiver at the 135-ft range. At this power level a signal-to-noise ratio of 17.5 dB was measured in the full 10-MHz video bandwidth with a 10-MHz peak-to-peak sine wave deviation on the transmitter. Fig. 9 shows the system input and output waveforms with a 1-MHz square wave modulating signal at this same power level.

Extrapolation of these results indicates that the same performance could be expected at a range of approximately 1000 ft or 300 m if the full power of the IMPATT oscillator were used in the transmitter. These measurements are somewhat conservative, however, and do not represent the maximum usable range of the system. Meaningful measurements at lower signal levels were not possible due to severe multipath effects in the building.

VII. Conclusions

The result of the present effort has been the development of a breadboard 60-GHz communication transmitter and receiver. Both units make extensive use of MILIC components in the RF sections. Active components in dielectric waveguide make possible a completely MILIC transceiver. Tests on the completed transmitter–receiver have demonstrated the feasibility of the approach. A maximum range of about 200 m has been achieved with a 40-MHz bandwidth and a 15-dB signal-to-noise ratio. However, it is felt that the range can be increased by reducing some of the MILIC circuit losses and the receiver noise figure, and increasing the antenna gains.

The transmitter–receiver modules developed under the present effort are the first of their kind utilizing the MILIC technology. It is expected that the next generation of systems will provide significant improvements and also will use active devices mounted in the dielectric waveguide. In addition, the various MILIC components developed at 60 GHz can be scaled to the 100-GHz region. Recent trends indicate that the band of frequencies around both 60 and 94 GHz will be important in satisfying future short-range communication and radar needs [9].

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