A Low-Cost 20–22 GHz MIC Active Receiver/Radiometer

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Abstract— **A microwave integrated circuit active receiver is built and tested at 19–25 GHz. The receiver consists of a planar CPW-fed double folded-slot antenna coupled to a six-stage MESFET amplifier and followed by a planar Schottky-diode detector. The folded-slot antenna on a GaAs half-space results in a wide frequency bandwidth suitable for MMIC amplifiers. The measured system performance show a video responsivity close to 1 GV/W at 20 GHz with a 3-dB bandwidth of 1500 MHz. A novel method which uses the planar video detector after the amplifier stages as an RF mixer is used to measure the noise-figure of the direct detection radiometer. The system noise figure is 4.8 dB at 22 GHz. The radiometer sensitivity to a hot/cold load is 3.8 μV/K. The measured antenna patterns show a 90%Gaussicity at 20–22 GHz. The active MIC receiver can be integrated monolithically for low-cost applications and is well suited for millimeter-wave linear imaging arrays.**

I. Introduction

INTEGRATED-CIRCUIT receivers consisting of a planar antenna integrated with a planar amplifier offer an advantage over the waveguide-based receivers at millimeter-wave frequencies. They are smaller, lighter and less expensive to build than waveguide systems, and can be easily produced in large numbers for millimeter-wave applications. In recent years, there has been a tremendous advance in MMIC amplifier technology and it is currently possible to build receivers based on direct detection (amplifiers) from 18–100 GHz with high gain and low-noise figure [1]. Most direct detection receivers have since been fabricated with the tapered slot antenna (TSA) which allows the easy fabrication of two-dimensional imaging arrays [2], [3] . A well designed TSA on a low dielectric constant substrate suffers from about 0.5 dB loss from the cross-polarization component in the 45°-plane and a somewhat lower coupling efficiency in an imaging system due to higher sidelobe levels [4], [5]. Also, it is very hard to build TSA on GaAs substrates at 30–94 GHz [2], [6] due to substrate-mode problems associated with the high dielectric constant of GaAs. Therefore, the TSA are built on thin Kapton films and are mechanically assembled with the millimeter-wave amplifiers. This increases the cost of the fabrication process of large mm-wave imaging arrays.

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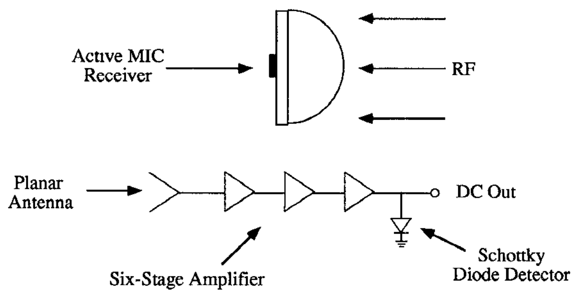


Fig. 1. Layout of the uniplanar active receiver/radiometer with a double-folded slot antenna and silicon substrate lens.

In order to circumvent the radiation properties associated with the TSA and very thin GaAs wafers, we have decided to base the radiometer on the coplanar-waveguide (CPW)-fed double folded-slot design. The folded-slot antenna on a GaAs half-space results in a wide frequency bandwidth. It is placed on an extended hemispherical silicon substrate lens to result in high gain patterns and high Gaussian coupling efficiency [7]–[9]. The high-efficiency planar antenna is followed by a six-stage MESFET amplifier and a CPW Schottky-diode detector circuit to result in a high-gain active receiver (Fig. 1). The CPW ground planes are equalized using wire bonds and the design requires no via holes or a backing ground-plane. The GaAs substrate is therefore not thinned down to 200 μm (or less at 94 GHz), and this increases the yield of the fabrication process. A simple transition, modeled as a series inductor, is used between the CPW-line and the microstrip-based MMIC amplifier chips. The MIC can be easily scaled to higher millimeter-wave frequencies, and can be monolithically fabricated in linear imaging arrays for remote-sensing, automotive collision-avoidance or landing systems applications.

II. Antenna and Receiver Design

The CPW-fed double folded-slot antenna is shown in Fig. 2(a). In this design, the length of the slot controls the H-plane pattern and the separation between the slot antennas controls the E-plane pattern. The slot antennas are chosen to be $0.48\lambda_m$-long (2.55 mm) with a separation of $0.34\lambda_m$ (1.85 mm) at 22 GHz where $\lambda_m = \lambda_0/\epsilon_m$ and $\epsilon_m = (1+\epsilon_r)/2$ is the effective dielectric constant in the CPW transmission-line. An important property of the folded-slot antenna is that the electric fields in the CPW-line at one side of the folded-slot are 180° out-of-phase with the electric fields on the other side of the folded-slot antenna (Fig. 2(b)). This is because the

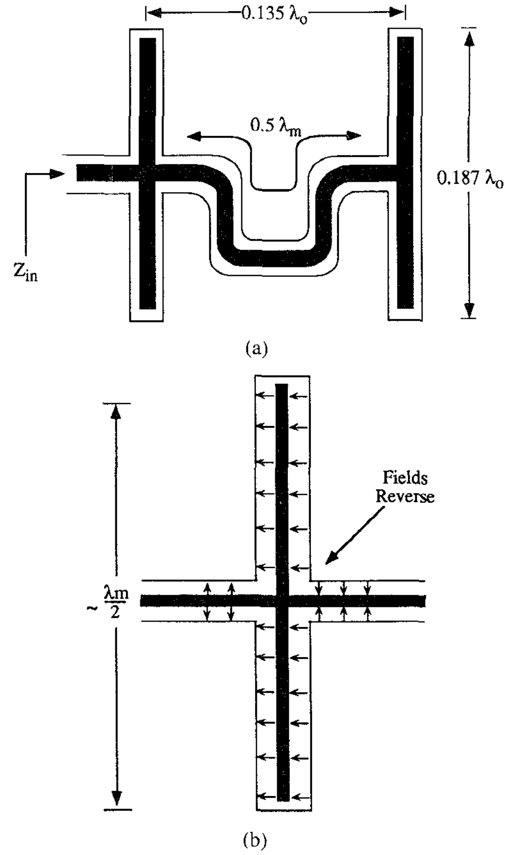


Fig. 2. The double folded-slot antenna design on a (a) GaAs half-space and (b) the field distribution around a folded-slot antenna.

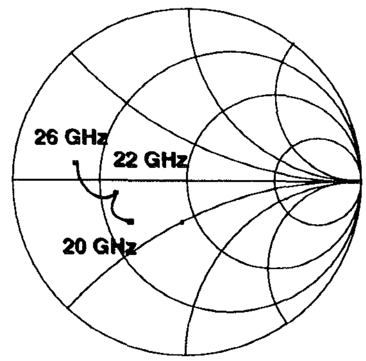


Fig. 3. The measured input impedance of the double folded-slot antenna design shown in Fig. 2.

folded-slot antenna can be modeled as a $\lambda_m/2$ transmission-line between the input and output ports [10]. This property is important because a meander CPW-line of total length equal to $\lambda_m/2$ is needed between the folded-slot antennas so as to feed the antennas in phase. This is considerably shorter than the meander CPW-line of total length equal to λ_m which is needed for standard double-slot antennas. The in-phase feeding results in a symmetrical pattern with a 10-dB beamwidth around 120° and an associated directivity of 10 dB *inside* the silicon dielectric lens. The dielectric lens increases the directivity of the antenna and eliminates the power loss to substrate modes [11]. The power radiated to the back-side is minimal, only 9–10% (−0.45 dB), and therefore no backing cavity is used to recover this power loss.

The double folded-slot antenna has been experimentally optimized using a microwave model to yield a wideband input impedance around 22 Ω over a ±20% bandwidth (Fig. 3). A full theoretical analysis of this antenna is presented in [12], [13]. Quarter-wave transformers are used to translate this impedance to 50 Ω which is the noise match of the MMIC amplifiers. The amplifier chain consists of three chips each containing a two-stage internally-matched low-noise microstrip amplifier. The MMIC amplifiers are fabricated by Martin Marietta Laboratories and provided to us by the John Hopkins Applied Physics Laboratory. The amplifier chip is a 100-μm-thick GaAs substrate and uses 0.1-μm HEMT technology. The amplifiers are hybrid mounted over the ground plane of the CPW line using silver epoxy. It is important to note that in a monolithic implementation, the antenna and amplifiers are integrated on a thick GaAs substrate in a CPW layout. The substrate is then placed on the Silicon lens and no thinning of the substrate is needed.

The measured performance of a single amplifier chip shows a wideband gain above 14 dB from 12–26 GHz, with an associated noise-figure of 2–3 dB from 22–28 GHz. A simple CPW to microstrip transition is used to connect the slot-antenna output to the amplifier chips. The bond-wire is 100 μm long with an estimated inductance of 0.1 nH at 22 GHz. The output of the first and second amplifier chips is connected to the following amplifier chip using a short bond-wire (100 μm).

A uniplanar Schottky-diode video detector is integrated after the last amplifier stage. The Schottky diode is an HP-HSCH-5230 beam-lead diode and is attached to the planar MIC using silver epoxy. The measured diode dc parameters are $R_s = 9\ \Omega, n = 1.06$ and $I_s = 5.7 \times 10^{-10}$ A with an estimated parasitic capacitance of 30 fF and series inductance of 0.15 nH. The diode is biased using the top layer of an overlay capacitor. The bias current is 20 μA and results in a junction capacitance of 80 fF and a junction resistance of 1400 Ω. The diode is in series with a CPW matching network composed of a 20° section with an impedance of 50 Ω and two shorted 70-Ω stubs with an electrical length of 35° designed for 22-GHz center frequency. The diode is very well matched at 22 GHz with a responsivity of 4000 V/W and has a 3-dB bandwidth between 18 and 26 GHz.

III. Receiver Measurements

The MIC circuit is fabricated by evaporating 4000 AA of gold on a 500-μm high-resistivity GaAs substrate. A 2-μm polyimide layer is used as the dielectric in the video-detector MIM bias capacitor. The CPW ground plane is not interrupted so as to preserve the radiation properties of the folded-slot antenna and the bias lines to the amplifiers are integrated on the polyimide layer which is spun over the CPW ground plane. The microstrip amplifier chips and Schottky diode detector are attached using silver epoxy. Bond-wires are used throughout the CPW line to equalize the ground planes. A picture of the completed receiver is shown in Fig. 4. The drain bias is 1.1 V and the gate bias pad is 0.1 V for each amplifier chip. Optimization of the bias for each stage to result in the

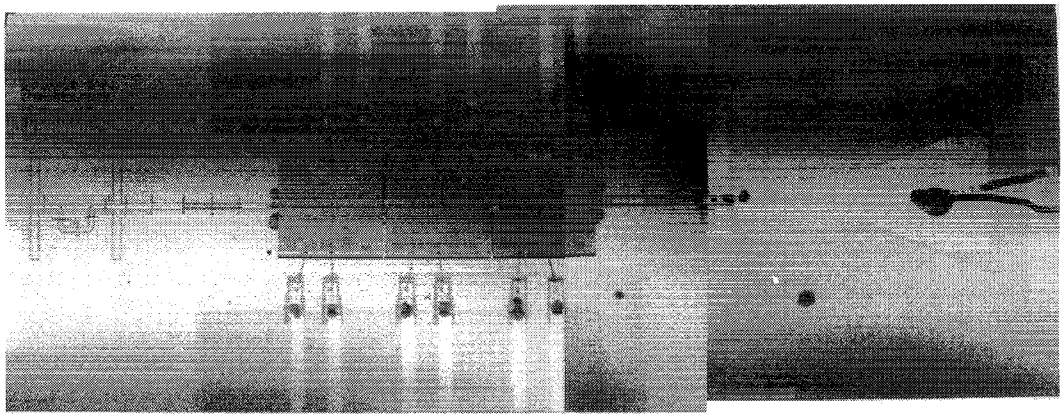
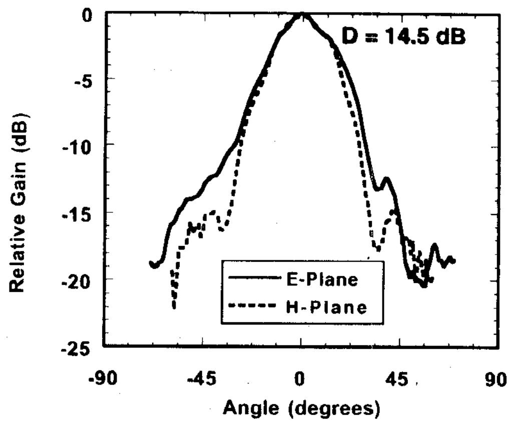


Fig. 4. The fabricated MIC active receiver/radiometer. The dimensions of each MMIC chip is approximately 2.2 mm-square.

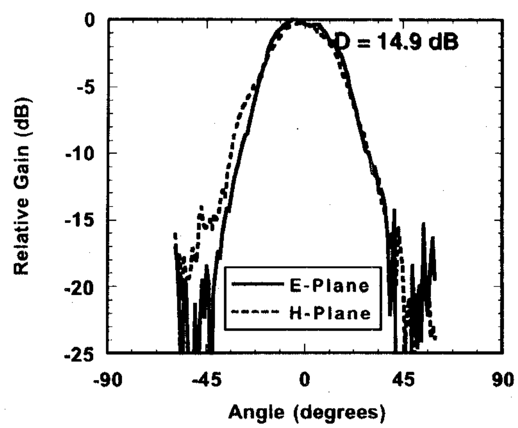
minimum noise figure or the maximum gain was not done. The MIC was aligned to the center of a 2.54-cm-diameter silicon lens at the elliptical position [8]. A matching cap layer is not used at the lens-air interface, thereby suffering approximately a 1.9 dB loss [8]. The measured antenna patterns at 22 GHz (Fig. 5(a)) show a Gaussian pattern with no sidelobes and directivity of 14.9 ±0.3 dB calculated by averaging the E, H, and 45°-plane patterns. The cross-polarized component was lower than −20 dB in the principal planes which indicate that the CPW meander line does not suffer from radiation loss. The directivity corresponds to an aperture efficiency of nearly 90% due to the small size of the lens used (1.8 λ_0). A higher directivity can be attained with a larger dielectric lens with an approximate aperture efficiency of 80% (see [8] for more details). The measured patterns at 20 GHz show an asymmetrical E-plane pattern. This is expected since the meander line between the folded-slot antennas is not $\lambda_m/2$ at this frequency and this results in a different phase for the two folded-slot antennas.

The measured voltage from the Schottky-diode video detector versus frequency is shown in Fig. 6. In this experiment, a plane wave of calibrated power density is incident on the aperture of the 2.54-cm-diameter lens and the detected diode voltage is recorded. The response includes the effect of the aperture efficiency of the double folded-slot/lens antenna (coupling to a plane wave, 80–90% at 20–22 GHz), the lens-air reflection loss, the six-stage amplifier and the Schottky-diode video detector. It is seen that the measured response of 965 MV/W peaks at 20 GHz with a 3-dB bandwidth of 1500 MHz. This results in an estimated six-stage "amplifier gain" of 55 dB at 20 GHz when the lens aperture efficiency at 20 GHz (around 85%), the lens-air reflection loss (1.9 dB), the back-side power loss efficiency (90%) and the video detector responsivity (4000 V/W at 20 GHz) are taken out of the measurements. The "amplifier gain" is defined as the available power at the output of the amplifier stage (to the Schottky-diode video detector) divided by the available power at the input of the amplifier stage (from the CPW port of the double folded-slot antenna).

The video responsivity shows a 10 dB drop at 22 GHz. This is unexpected since the antenna response, the amplifier gain and the diode video responsivity are all designed to be centered at 22 GHz and have a wideband frequency response. We believe that the drop in responsivity is due to the Schottky video detector. The matching network from 1400 Ω (the junction resistance at a bias of 20 μA to 50 Ω is very sensitive to the values of the junction and parasitic capacitances. A small increase in these capacitances (30–50 fF) due to the silver epoxy results in a diode match at 17–18 GHz and a much lower video responsivity at 22 GHz.



(a)



(b)

Fig. 5. The measured far-field patterns at (a) 20 and (b) 22 GHz. The silicon substrate lens is 2.54 cm in diameter.

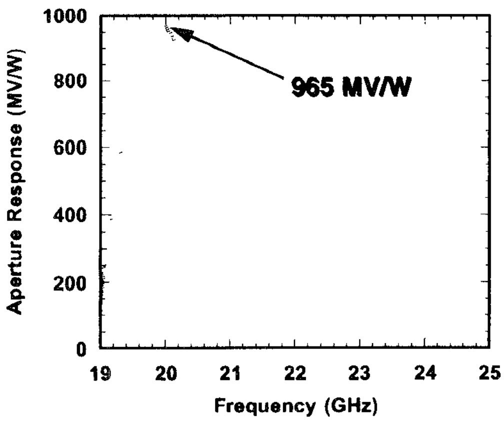
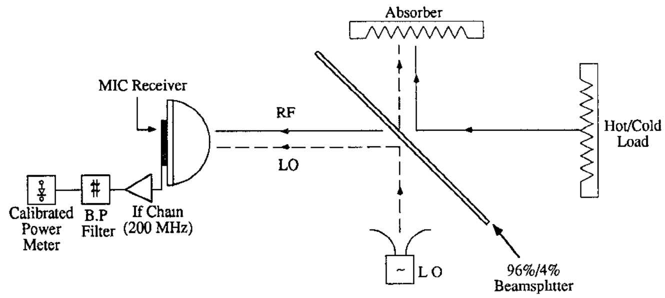


Fig. 6. The measured system video responsivity versus frequency. The 3-dB bandwidth is 1500 MHz.

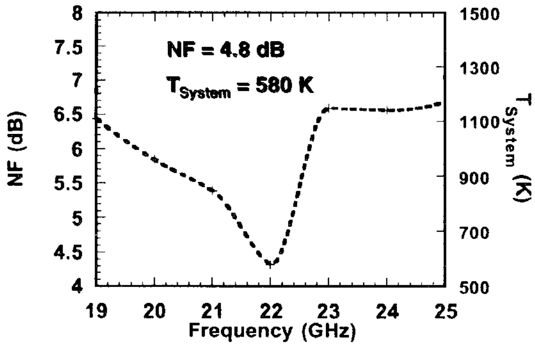
The response of the planar radiometer to a hot/cold load is measured by placing a cold absorber in front of the receiver and using a chopper with a hot load attached to its blades. The measured rms value is 3.8 μV/K at a 10 Hz chopping frequency. Using the formula, $\Delta V = R\Delta P = RKGB\Delta T$ and the values given for the estimated video responsivity R (4000 V/W at 20 GHz), the bandwidth B (1500 MHz) and the Boltzman constant K, the resulting "system gain" of the radiometer is calculated to be 47 dB. The "system gain" includes the 2 dB lens-air reflection loss, and therefore the estimated " amplifier gain" is 49 dB. The discrepancy with the above-mentioned measured value is probably due to different biasing conditions (the experiments were not done at the same time and same biasing conditions) and to a lower average gain over the 3-dB video bandwidth. The stability (and noise floor) of the radiometer system was not measured and is expected to be less than optimal since a biased Schottky-diode detector is used (with its associated large $1/f$ noise). In the future, a zero-bias planar PDB diode [14] could be used to eliminate the $1/f$ noise problem and still result in a large video responsivity.

IV. Noise Figure Measurements

A novel approach has been used to measure the noise figure of the MIC receiver (Fig. 7(a)). In this method, a 19–25 GHz local oscillator is injected quasi-optically using a 4% beamsplitter. The local oscillator is received by the planar antenna, amplified by the six-stage MMIC chain and delivered to the video detector. Care must be taken that the right amount of LO power is injected into the radiometer system so as to drive the video detector non-linearly (0.5–1 mW) but also not to drive the last amplifier stage into saturation (5–10 mW) and therefore considerably increasing its corresponding noise power. This is done by changing the injected amount of LO power and monitoring the dc bias on the video detector. The radiometer system is also subjected to a hot/cold load RF signal using the 96% beamsplitter. The RF signal is picked up by the planar antenna, amplified using the six-stage MMIC chain and delivered to the video detector. The RF signal mixes with the injected LO signal at the diode detector and the IF signal (200 MHz) is taken out from the bias network. The IF signal feeds into a 90 dB IF chain, a 200 MHz bandpass filter



(a)



(b)

Fig. 7. The noise measurement setup for (a) the direct detection radiometer and (b) the measured system noise figure versus frequency.

with a 20 MHz passband and a calibrated 200 MHz power meter.

It is true that the video detector is not a good mixer (10–15 dB conversion loss at 22 GHz) and that some attenuation of the IF signal will occur on the bias line, but the mixer is preceded by a low-loss planar antenna and a 50 dB MMIC amplifier chain. Using this technique and varying the LO frequency, the noise figure of the radiometer system was measured (Fig. 7(b)). It is seen that a 4.8 dB noise figure is measured at 22 GHz. Notice that the noise figure is minimum at 22 GHz and not at 20 GHz where the system responsivity peaks at 965 MV/W. This confirms our belief that the drop in the system responsivity at 22 GHz (see above) is due to the Schottky-diode video detector. In the noise figure experiment, the video detector/mixer is preceded by a 50 dB amplifier stage and has no effect on the noise-figure measurement. The receiver noise figure is entirely dominated by the planar antenna loss and the first stage of the MMIC amplifier chain.

The measured 4.8 dB system noise figure can be broken down into 2.3 dB amplifier noise, 2.0 dB antenna loss due to the reflection loss at the lens-air interface and 0.5 dB antenna loss due to radiation to the back-side. If a matching cap is used, the noise figure is expected to be reduced by approximately 1.6–1.9 dB [9]. This has been experimentally observed by several groups at mm-wave frequencies using lens-coupled Schottky-diode or SIS detectors [15]. Notice than in this experiment, a primary lens (or objective lens) in front of the folded-slot/lens antenna is not used due to its large size at 22 GHz. In a radiometer system with a primary lens, the noise figure is expected to increase by about 0.5–0.7 dB due to the 85–90% pattern Gaussian coupling efficiency of the folded-slot/lens system.

V. Conclusion

A low-cost MIC active receiver with high system gain has been demonstrated at 20–22 GHz. The approach consists of integrating a new planar antenna, the double folded-slot antenna, together with the low-noise MMIC amplifiers and a Schottky-diode video detector. The design is based on uniplanar CPW line technology and requires no via-holes processing or wafer thinning. A novel method to measure the noise figure of a direct detection radiometer is presented and the results agree well with the predicted values. The MIC can be easily scaled to higher millimeter-wave frequencies, and can be monolithically fabricated in single elements or linear imaging arrays ($1 \times N$ or $2 \times N$ arrays) for low-cost applications.

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