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A 75 GHz to 115 GHz Quasi-Optical Amplifier

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ABSTRACT

A wideband quasi-optical amplifier employing two pyramidal back-to-back horns has been developed. Using a four-stage W-band low noise amplifier (LNA) designed and fabricated by Martin Marietta Laboratories [1], the quasi-optical amplifier gives a system gain greater than 11 dB from 86 GHz to 113 GHz without any low frequency oscillations. A peak system gain of 15.5 dB is measured at 102 GHz, and the measured noise figure of the system is 7.4 dB at 94 GHz. The quasi-optical amplifier design maintains the same polarization of the received and transmitted signal while providing good isolation and can be fabricated monolithically at millimeter-wave frequencies.

INTRODUCTION

Recent advances in transistor technology at Martin Marietta Laboratories have led to the development of a four-stage W-band low noise amplifier (LNA) using pseudomorphic InGaAs Modulation-Doped Field Effect Transistors (MODFET's). These amplifiers have demonstrated gains up to 23 dB in a waveguide environment [1]. The amplifiers typically employ a waveguide-to-microstrip or waveguide-to-coplanar waveguide transition [1], and the waveguide test fixture is expensive to build at frequencies higher than 100 GHz. It is therefore advantageous to incorporate these amplifiers directly within a radiating structure that can be fabricated monolithically and can be easily scaled to frequencies higher than 100 GHz.

This approach has been done at lower frequencies by Kim et al. [2] and Chi et al. [3]. In both techniques, the quasi-optical amplifier employ polarization diplexing and a differential amplifier stage. In this paper, a new quasi-optical amplifier design based on the integrated horn structure [4] is presented. There is no need for tuning polarizers and therefore this design allows a wide operating bandwidth. The design maintains the same polarization and is compatible with very high gain monolithic millimeter wave amplifiers.

QUASI-OPTICAL AMPLIFIER DESIGN

The quasi-optical amplifier consists of two back-to-back pyramidal horns each with openings of $1.35\lambda_o$ x $1.35\lambda_o$ at the design frequency of 94 GHz. A 4.25 mm x 1.25 mm Martin Marietta Laboratories LNA chip is placed approximately $\lambda_o/2$ above the apex of each pyramidal horn (Fig. 1a). Two back-to-back pyramidal horns are fabricated by anisotropically etching <110> silicon wafers from opposite sides and stacking eight 385 μm-thick horn sections and one 200 μm cavity spacing section. The LNA is hybrid mounted in the etched cavity connecting the two integrated horns (Fig. 1b). The cavity is 3.0 mm wide by 200 μm high. The thickness of the LNA GaAs substrate is 100 μm. The sidewalls of the horns and the sides of the cavity are metallized with 0.7 μm of gold through angle evaporation.

The position of the chip within the horn cavity is chosen using a 3 GHz (equivalent to 94 GHz) microwave scale model for a probe of length 600 μm and width of 190 μm on a 100 μm thick GaAs substrate (at 94 GHz). An input match (S_{11}) better than -20 dB from 2.75 GHz to 3.25 GHz (equivalent to 86.5 GHz to 102 GHz) is measured with the probe facing the interior of the horn - the input horn (Fig. 2a). An input match better than -10 dB is measured with the probe facing out of the horn - the output horn - over the same frequency range (Fig. 2b). The probe radiates preferentially into the dielectric side, thereby resulting in a better match for the input horn.

The LNA is mounted on a silicon wafer containing the bias lines, bias resistors and bypass capacitors (Fig. 3). The four gates are biased at 0.25 V. The drains are biased separately and optimized for maximum gain. The bias voltages for the drains, from input to output, are 4.5 V, 3.8 V, 3.5 V, and 3.5 V, respectively. The total source-to-drain current for all four MODFET's is 24 mA. The source is grounded on the back side of the LNA chip along the receiving horn sidewall using silver epoxy and 0.7 mil gold ribbon.

MEASUREMENTS

Patterns taken from a 3 GHz microwave model show a very high cross- polarization level of both the input and output integrated horns (Fig. 4). This is attributed to the short length and large width of the waveguide-to-CPW probe. Since the probe dimensions of the LNA are fixed, we are not able to decrease the cross-polarization level. We recommend that a longer narrower probe be used for future quasi-optical amplifier applications which will result in reduced cross-polarization levels [6]. The short monopole probe also results in an asymmetry in the E-plane copolarization pattern. No pattern measurements are done at other frequencies, but the same behavior is expected over the 2.75-3.25 GHz band (equivalent to 86.5 GHz to 102 GHz). Notice that the input pattern is better than the output pattern because the monopole probe radiates preferentially into the dielectric side of the substrate.

The gain of the quasi-optical amplifier structure is measured in a plane-wave experiment similar to [2]. First, the system is calibrated without the quasi-optical amplifier present. The power received during calibration, P_c, is determined from Frii's transmission formula:

$$\mathrm{P}_c = P_t \left(\frac{G_t G_r}{4\pi (2r)^2} \right) \tag{1}$$

where $2r$ is the distance between the transmitting and receiving horns, P_t is the transmitted power, G_t is the gain of the transmitting antenna (a WR-10 pyramidal horn), and G_r is the gain of the receiving antenna (a WR-10 pyramidal horn). Next, the power received, P_r, with the quasi-optical amplifier in place is given by:

$$P_r = P_t \left(\frac{G_t A^{eff}_{input}}{4\pi r^2} \right) G \left(\frac{G_r A^{eff}_{output}}{4\pi r^2} \right) \tag{2}$$

where G is the gain of the LNA, A^{eff}_{input} is the effective aperture area of the input horn, A^{eff}_{output} is the effective aperture area of the output horn and r is the distance between the transmitting or receiving horn and the quasi-optical amplifier. Since the effective apertures of the input and output integrated horns are not known accurately, the aperture efficiencies are separated from the physical area of the input and output integrated horns:

$$P_r = P_t \left(\frac{G_t \varepsilon^{eff}_{input} A_{phys.}}{4\pi r^2} \right) G \left(\frac{G_r \varepsilon^{eff}_{output} A_{phys.}}{4\pi r^2} \right) \tag{3}$$

where A_{phys} is the physical area of the input and output horns, $\varepsilon^{eff}_{input}$ is the effective aperture efficiency of the input horn, and $\varepsilon^{eff}_{output}$ is the effective aperture efficiency of the output horn. The gain of the quasi-optical system, G_{SYS}, is then found by dividing (1) by (3) and solving for $G\varepsilon^{eff}_{input}\varepsilon^{eff}_{output}$.

$$G_{SYS} = G\varepsilon^{eff}_{input}\varepsilon^{eff}_{output} = \left(\frac{P_r}{P_c} \right) \left(\frac{\lambda r}{2A_{phys.}} \right)^2 \tag{4}$$

The system gain is measured over the frequency range of 75 GHz to 115 GHz. The gain of the quasi-optical amplifier, G_{SYS}, is greater than 11 dB from 85 GHz to 113 GHz and greater than 3 dB gain from 75 GHz to 115 GHz (Fig. 5). No oscillations are found on the bias lines or in free space and isolation is perfect when the bias is removed. The dips and peaks of the gain curve occur because the antenna pattern and cross-polarization levels change with frequency. From microwave pattern modeling, we expect the co-polarized aperture efficiency of each horn to be below 60% at 94 GHz. Thus the lower limit of the gain of the amplifier chip itself would be at least 4 dB above the curve in Figure 4. Although the exact gain of the LNA is not known, histograms of the gains of 44 different LNA's fabricated at the same time suggest a mean LNA gain of 16.3 dB around 90 GHz and a standard deviation of 3.2 dB.

This value corresponds closely with the measured system gains of 12.9 dB at 94 GHz and 15.5 dB at 102 GHz. If the effective aperture efficiencies were deembedded from the gain calculation, the gain would increase by more than 4 dB to 16.9 dB at 94 GHz.

Figure 6 displays the experiment for measuring the noise figure of the quasi-optical amplifier. The IF chain gain and input noise temperature is measured to be 97.0 dB and 55.3K, respectively, at 94 GHz. The conversion loss of the balanced mixer is measured to be 4.6 dB with a mixer input noise temperature of 821K. The loss of the teflon lens (f/D=0.85) is determined to be 0.30 dB. Next, we measure the noise figure of the quasi-optical amplifier to be 7.4 dB at 94 GHz using standard hot/cold load techniques. This value matches with an expected 7-8 dB noise figure from these specific LNA's. New LNA's from Martin Marietta Laboratories that have 23 dB gain and 4.3 dB noise figure [1] would greatly improve the performance of the quasi-optical amplifier.

CONCLUSIONS

In this paper we report a single element quasi-optical amplifier that is based on an integrated horn antenna using a LNA originally designed for operation within waveguide. Using the waveguide-to-CPW probe as the radiating element for the structure, a peak system gain of 15.5 dB at 102 GHz is measured and higher than 11 dB system gain is measured over a 27% bandwidth. The quasi-optical horn antenna can be designed to result in a much lower cross-polarization level using a long monopole probe and to couple efficiently to a Gaussian beam system using an integrated horn extension [4]. The quasi-optical amplifier maintains the same polarization of the incoming and outgoing signal. The absence of tuning polarizers allow a wider operating bandwidth for this design.

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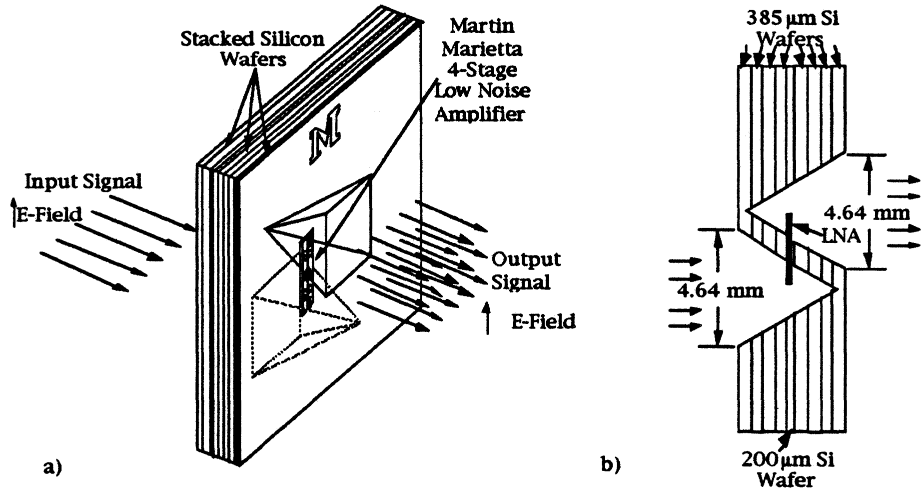

Figure 1: Quasi-optical amplifier consisting of Martin Marietta Laboratories' low noise amplifier between two back-to-back pyramidal horns. A plane wave input signal is amplified and repeated on the opposite side with the same polarization. a) Isogonal view. b) Side view.

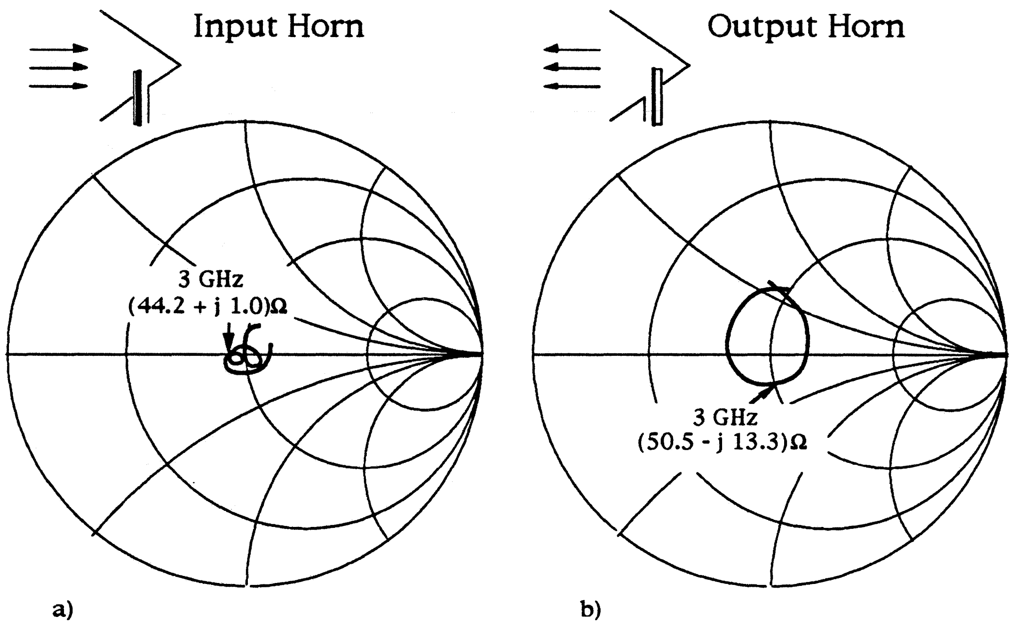

Figure 2: a) Input impedance of monopole inside the input pyramidal horn of a microwave model measured from 2.75 GHz to 3.25 GHz (equivalent to 86.5 GHz to 102 GHz). b) Input impedance of output pyramidal horn of quasi-optical amplifier microwave model measured from 2.75 GHz to 3.25 GHz.

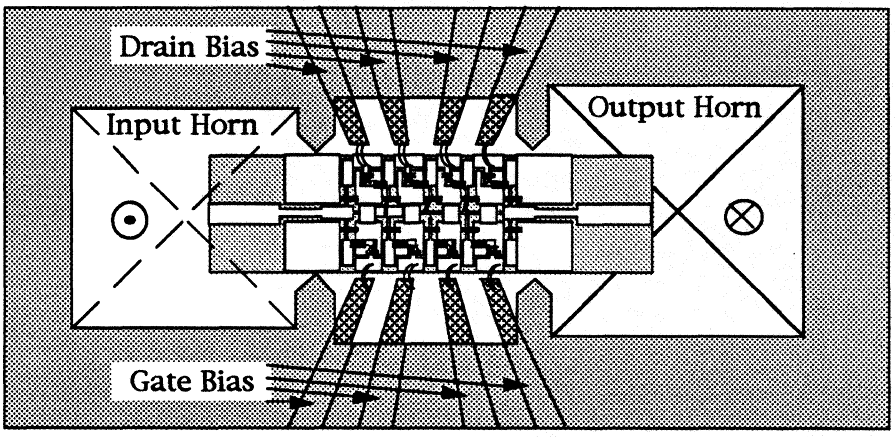

Figure 3: Martin Marietta Laboratories' low noise amplifier (LNA) chip placed in a cavity between two horn openings. Eight bias lines supply voltage to the four drains and gates while the source is grounded from the back side of the LNA chip. The LNA chip dimensions are 4.25 mm by 1.25 mm.

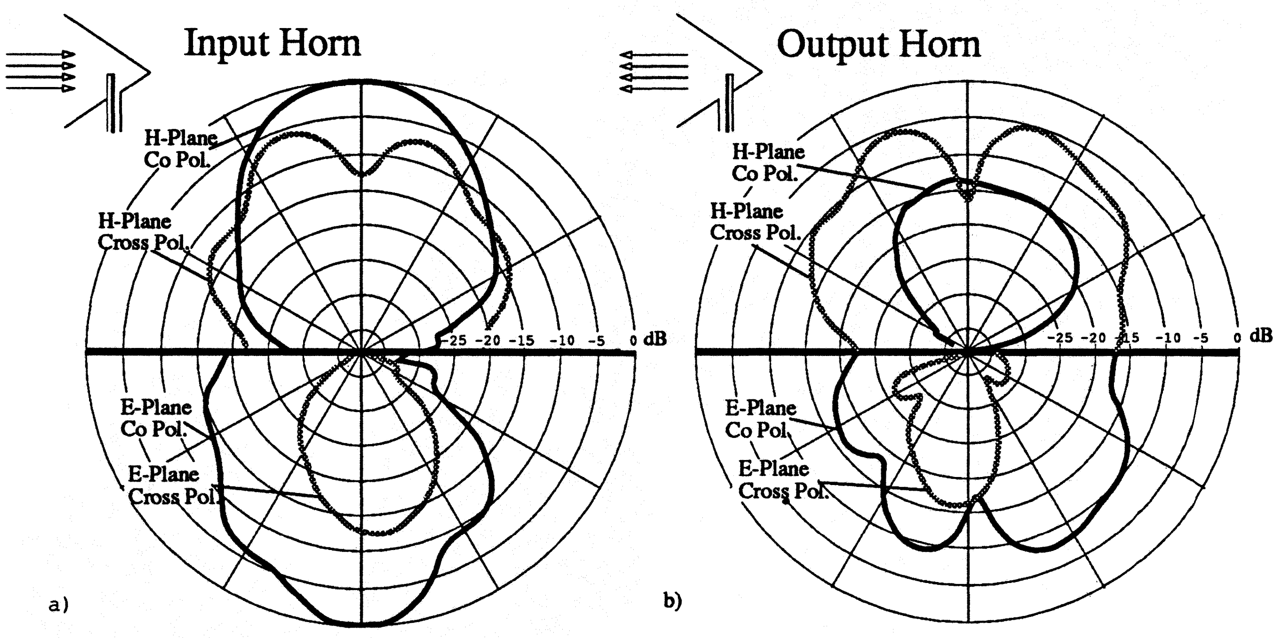

Figure 4: Quasi-optical amplifier 3 GHz microwave model (equivalent to 94 GHz) antenna patterns. a) Antenna patterns with monopole facing the interior of the horn. b) Antenna patterns with monopole facing the exterior of the horn.

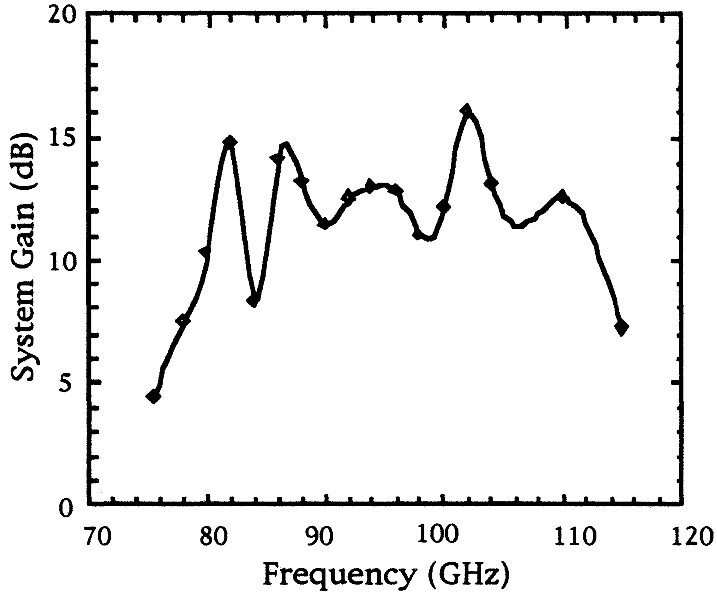

Figure 5: Quasi-optical amplifier system gain versus frequency. The system gain includes loss due to input and output horn aperture efficiency. The peaks and dips in the plot are due to the changing cross-polarization levels and antenna patterns with frequency.

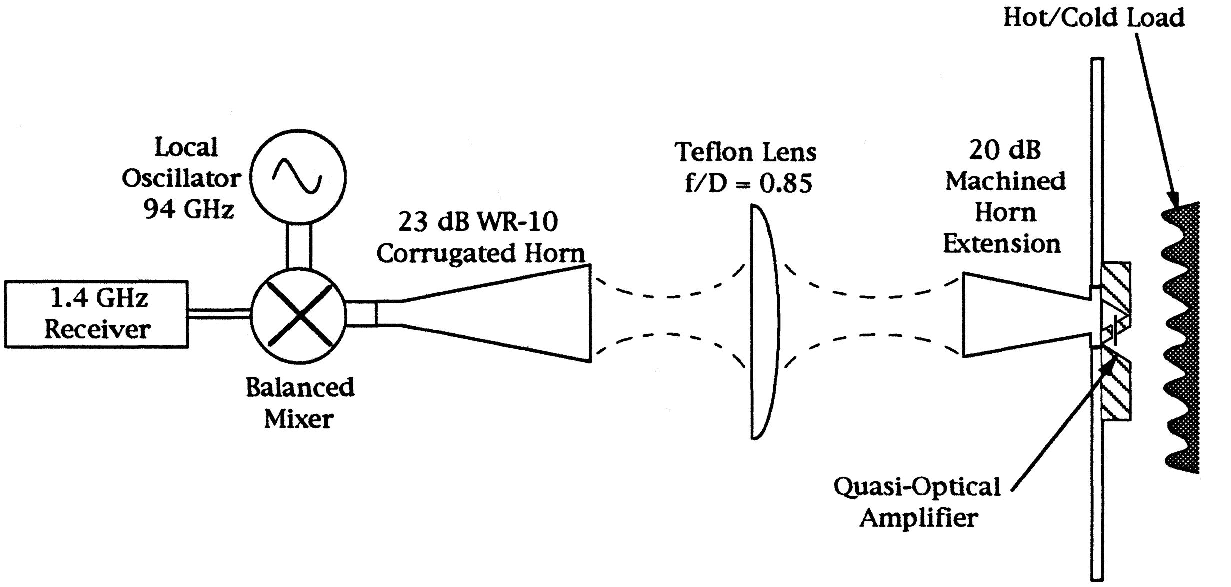

Figure 6: Noise figure experiment using an LO frequency of 94 GHz and an IF of 1.4 GHz.