A Microstrip-Based Unit Cell for Quasi-Optical Amplifier Arrays

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***Abstract*—A microwave scale model of an amplifying element suitable for millimeter-wave quasi-optical arrays is presented. Power is guided into the amplifier by short sections of waveguide and then fed into a microstrip based MESFET amplifier with an E-field probe. A second E-field probe couples the output signal into a similar waveguide feed on the back-side of the element. The output waveguide is orthogonal to the input to achieve isolation.**

I. Introduction

IN A quasi-optical amplifier array, the power limitations of single semiconductor devices are overcome by distributing the power across many devices [1]–[6]. A major challenge in the design of these arrays is the electromagnetic modeling required to obtain optimal performance. The problem can be simplified with a design in which unit cells of the array are electrically isolated from each other and can therefore be modeled individually. With such a design, a cell can be individually tested, optimized, and then duplicated to create the quasi-optical array. However, the architectures of previous grid demonstrations make it difficult to isolate and test a single unit cell. In the approach presented here, short sections of waveguide which act as electric walls are used to isolate the cells (Fig. 1). This allows circuit ideas to be rapidly evaluated and optimized with relative ease.

As with previous demonstrations [1], [2], [4], the design presented here produces a free space output which is orthogonal to the input. This orthogonality allows the output signal to be confined to one side of the array and, by reciprocity, leads to efficient coupling of the input signal. Another advantage of the design is that the metallic rectangular waveguides act as heat-sinks, helping to dissipate the heat generated by the amplifiers. This design also allows for the unit cell to be optimized at microwave frequencies, where testing and design is easier, before scaling up to millimeter-wave frequencies.

This letter reports on the results of an amplifier unit cell operating in the 3.95 to 5.85 GHz waveguide band (WR-187) with a microstrip-based amplification section. Because microstrip technology is well characterized up to modest millimeter-wave frequencies, the amplification section design is straightforward. Furthermore, the source and load impedances of the amplification section are matched, so the microstrip amplifier can be independently designed and tested in a 50 Ω environment. The amplifier unit cell has a measured gain of over 12 dB at 4 GHz.

Manuscript received May 25, 1993. This work was supported by the Raytheon Company. N. J. Kolias is supported by a National Defense Science and Engineering Graduate Fellowship.

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IEEE Log Number 9211894.

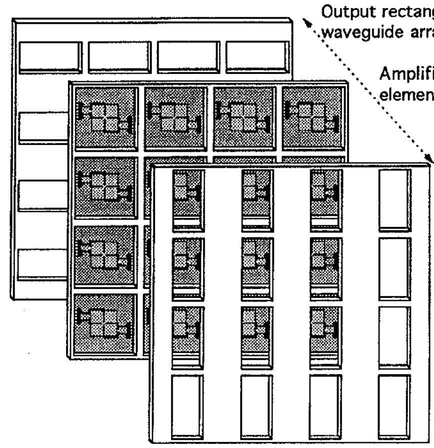

Fig. 1. Exploded view of the quasi-optical amplifier array. The output waveguides are rotated 90° with respect to the input waveguides.

II. Design

The amplifier cell, pictured in Fig. 2, evolved from the testing of several distinct designs. The incoming radiation enters through the vertically oriented rectangular waveguide on the left-hand side, while the amplified signal exits from the horizontally oriented waveguide on the right. The amplification element, shown on the right in Fig. 2, contains two planar microstrip amplifier circuits and is located inside a square waveguide, sandwiched between the input and output waveguides.

Incoming radiation incident from the left excites the TE_{10} mode in the input rectangular waveguide (WG1). This waveguide mode will also propagate in the adjoining square-waveguide (WG2), but will be cut-off in the waveguide on the right (WG3). The incoming radiation will pass through WG1 and will excite the two vertically oriented probe antennas of the amplification element. These probe antennas are patterned on a thin (25 mil) RT/Duroid substrate with a relative dielectric constant $\epsilon_r = 9.8$. The backside of the substrate is grounded except for a square area underneath the probe antennas. From each of the probe antennas, the radiation passes into a 50 Ω microstrip line which in turn feeds the gate of an Avantek 10 335 GaAs MESFET in common source configuration. The output at the drain of each MESFET propagates via microstrip to a horizontally oriented probe antenna. The radiated signal from the horizontal antennas can propagate in the square

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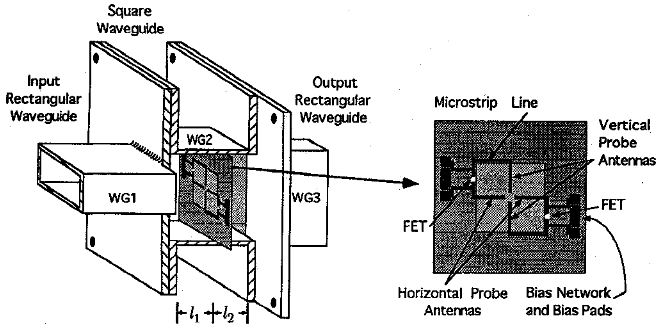

Fig. 2. The amplifier unit cell with the square waveguide cut open to show the amplification circuitry. The dimensions of square waveguide WG2 are 1.872 x 1.872 in. Waveguides WG1 and WG2 have dimensions of 1.872 x 0.872 inches. l_1 is the distance from the amplification circuitry to the start of the square waveguide, while l_2 is the distance from the amplification circuitry to the end of the square waveguide.

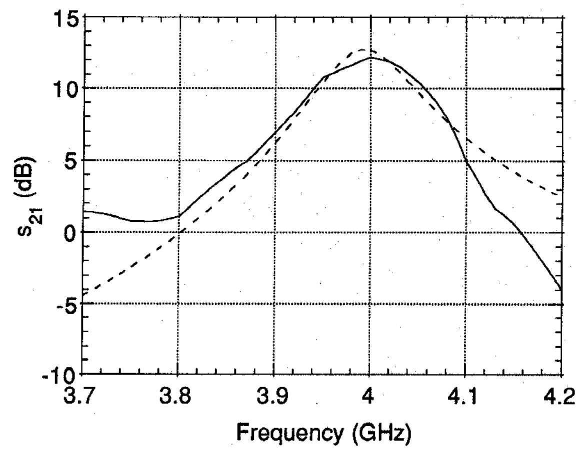

Fig. 3. Gain of the individual amplifying cell. — measured, - - - calculated.

waveguide and in the output waveguide (WG3), but will be cut-off in the input waveguide (WG1). Thus, the horizontally oriented amplified output signal can only travel to the right along WG3.

Incident power that is not coupled into the vertical probe antennas will be reflected back into the input by WG3 (which is cut-off for vertically polarized radiation). The amount of coupling into the probe antennas is determined by lengths l_1 and l_2 of the square waveguide (Fig. 2), as well as the lengths and widths of the probe antennas [7,8]. For maximum coupling, lengths l_1 and l_2 are chosen so that an electric field maximum exists at the plane of the probe antennas. With the square waveguide not present ($l_1 = l_2 = 0$), the probe antennas are close to an electric field minimum and therefore do not receive much coupled power. This electric field minimum occurs because, for the vertically polarized incident radiation, the crossed output waveguide effectively acts as a short circuit a small distance away from the probes. The length l_2 moves this short farther from the probes, thereby improving the coupling. The length l_1 does the same for the horizontally oriented output radiation.

To reduce the dc bias network's RF loading on the circuit, the gate and drain bias leads both pass through quarter-wavelength long stubs. These stubs are RF grounded through a 47 pF chip capacitor a quarter-wavelength from the circuit. The stubs were designed to be a quarter-wave long at 4.9 GHz. For the amplifier cell, the square waveguide lengths, $l_1 = l_2 = 5.1$ mm, were arrived at semi-empirically. The probe antennas are the same width as the 50-Ω microstrip lines, $w = 0.621$ mm. The total length of each probe antenna is 8.08 mm.

III. Measurement

An advantage of this design is that the cells can be directly tested using an HP 8510 vector network analyzer with coaxial-to-waveguide transitions. Using this method rather than a free-space measurement is justifiable since the square apertures in which the probes sit have been shown to have close to 100% efficiencies for plane wave coupling into the TE_{10} mode [9]. The coaxial-to-waveguide adapters can be de-embedded from the measurement by using a standard TRL calibration. With the present setup, the degree of feedback coupling between orthogonal probes cannot be accurately measured.

The measured gain, $|s_{21}|^2$, obtained using the network analyzer is plotted in Fig. 3. A 20-dB directional coupler connected to a spectrum analyzer was inserted into the output path to confirm that the amplifying element was stable. The amplifier has a peak gain of greater than 12 dB and a fractional 3-dB bandwidth of 3.5% at 4.0 GHz. The waveguide to E-field probe antenna transition currently limits this bandwidth. When tested in a microstrip test fixture, the microstrip amplifier alone displayed a large fractional bandwidth of approximately 30%. With the transistor replaced by a 50Ω through, an insertion loss of 0.9 dB and fractional bandwidth of 10% was measured. Since waveguide-to-coax probe transitions have demonstrated low insertion loss over entire waveguide bands, the cells described here should be capable of bandwidths approaching 40%. Further optimization of the probe dimensions and positioning are required to increase the unit cell's bandwidth.

The amplifier cell was modeled theoretically using a circuit model which consisted of the microstrip amplifier circuitry sandwiched between the two rectangular-to-square waveguide transitions, with each square waveguide being 5.1 mm long as in the actual amplifier cell. The only free parameter added to the circuit model was a parallel inductance, L, placed at each transition between the microstrip line and the square waveguide. This inductance represents the reactance due to the excitation of evanescent waveguide modes at the waveguide-probe discontinuity. A value of 1.78 nH for L was found to agree well with experimental measurements (Fig. 3). This value for L was also consistent with measurements on a unit cell where the transistors were replaced with straight through connections.

IV. Conclusion

A microstrip-based unit cell for a quasi-optical amplifier array has been presented. The cell has short sections of rectangular waveguide at the input and output which provide electrical isolation from adjoining cells, thereby enabling it to be designed, tested, and optimized individually. A microwave model of the unit cell yielded promising results, providing a gain of over 12 dB with a fractional bandwidth of 3.5% at 4 GHz.

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