# Planar Amplifier Array With Improved Bandwidth Using Folded-Slots

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***Abstract*— Active antennas on semiconductor substrates often suffer limited bandwidth. We report on a relatively broadband quasi-optical amplifier cell and 4×4 array using folded-slot antennas, suitable for monolithic power combining. Two orthogonally polarized cpw-fed folded slots are coupled to the input and output ports of a simple resistive feedback MESFET amplifier. The peak effective isotropic power gain in the transmission mode is 11 dB @ 4.3 GHz with 10% bandwidth for the single cell, a factor-of-ten improvement in bandwidth over a similar amplifier cell using patch antennas, and 32 dB @ 4.24 GHz with 8% bandwidth for the array.**

## I. INTRODUCTION

MONOLITHIC arrays of antenna-coupled amplifiers have been suggested for millimeter-wave applications demanding large output power, with low-noise, high-efficiency, and solid-state reliability. Such arrays could amplify beams in a quasi-optical system or in a closed waveguide. Free-space amplifiers have been reported using both the grid approach [1], [2] and arrays of conventional antennas such as the dipole and patch [3]–[5]. In principle, the grid concept permits a dense integration of devices and hence the potential for increased power/unit area over arrays using larger antenna structures. However, the small absorbing cross-section of the grid unit cell requires a large incident power density for high efficiency operation. Amplifier cells using conventional planar antennas have a larger effective area but typically suffer limited bandwidth, from 1–3%. In this paper, we report a broadband planar amplifier array and single cell using orthogonally polarized cpw-fed folded-slot antennas coupled to a resistive feedback single-stage MESFET amplifier. The folded slots give an order of magnitude improvement in bandwidth over a previously reported amplifier based on patch antennas [5] and can be used for either transmission or reflection amplification.

## II. AMPLIFIER AND ANTENNA DESIGN

Scale modeling at 4 GHz was used to simplify the amplifier measurements and device requirements. A simple resistive feedback amplifier was designed, using a packaged GaAs MESFET (NE32184A); this circuit is more stable and tolerant of device variations than the resonant matched amplifier. From the manufacturer's data sheet, the transconductance of this MESFET, $g_m$, is typically 33 mS. Let $R_f$ be the drain-gate feedback resistor, $A$be the voltage gain of the amplifier, and $Z_o$ be the source and load impedance. Using the design equations [6], [7]

$$g_m = \frac{1-A}{Z_o}, \quad R_f = Z_o(1-A) \tag{1}$$

leads to $Z_{in} = Z_{out} = Z_o$, where $Z_{in}$ and $Z_{out}$ are defined as the input and output impedances of this amplifier. This is convenient since identical antennas are coupled to the input and output of the amplifier. However, the gain and terminal impedance can not be specified arbitrarily. With $R_f$ =511Ω (a value readily available in our lab) and $Z_o$=125Ω, the voltage gain will be $A$ = -3.1, corresponding to ~10-dB power gain. This amplifier design was simulated on Libra [8] and the result shows that the gain is 8 dB @ 4 GHz and the 3-dB cutoff frequency of this feedback amplifier is approximately 6 GHz.

Rogers Duroid 6010 with a dielectric constant of 10.8 and thickness of 0.635 mm was used as the substrate material. The dielectric constant is close to that of GaAs, which will be used when we scale the amplifier to higher frequencies. Folded slots were chosen over other possible wideband antenna structures because they are simpler to make (one mask step), can be more easily integrated with three-terminal devices, can be used for reflection or transmission amplifiers, and are expected to have an input impedance on the order of 100 Ω, which is very close to that of the amplifier design described above. This impedance is expected from considerations of the complementary structure (the folded dipole [9]) and application of Booker's relation [10] using the mean dielectric constant (not strictly valid but a good engineering approximation).

There is very limited design information available for the folded-slot on dielectric substrates [11], so the dimensions of the antenna were determined empirically for operation at 4 GHz. A plan view of the complete amplifier cell is shown in Fig. 1. The dimensions of the folded slot are $L$=18mm, $W$ =7mm, and a gap width of 1 mm. The input impedance of this antenna is 180 Ω, which is consistent with the value in [11]. However, we were limited to a CPW feed characteristic impedance of 80 Ω. The resulting impedance mismatch between amplifier, CPW line, and antennas will thus degrade the amplifier performance. The simulation indicates that the amplifier gain drops to 6 dB with the mismatch instead of 8 dB with a perfect match. There are also several air bridges across the CPW line to ensure a constant ground potential and prevent the excitation of unwanted slot modes. A series resistor and bypass capacitors were used to apply gate

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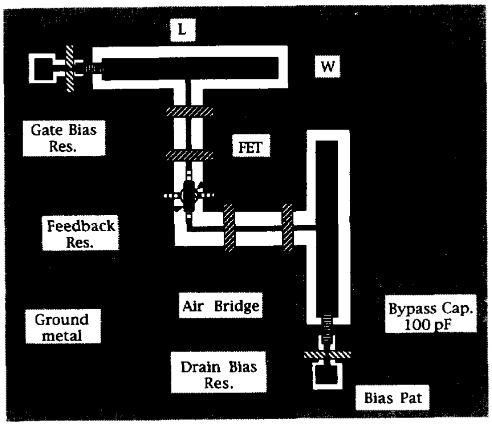

Fig. 1. Plan view of the folded-slot amplifier cell. The drain-gate feedback resistor is soldered piggy-back to the FET. Slot dimensions are given in the text.

and drain bias. As with previous amplifier designs [1]–[4], the input and output antennas were orthogonally polarized to avoid mutual coupling between input and output which could lead to oscillation. The amplifier array consists of 16 such amplifier cells arranged in 4×4 format with approximately half wavelength spacing in each direction.

## III. MEASURED RESULTS

The bi-directional radiation characteristics of the folded slot antenna allows the circuit to be used as either a transmission amplifier or a reflection amplifier (the latter requires a mirror behind the amplifier). Both configurations were tested for the single-cell case. For the reflection amplifier, an aluminum sheet was placed behind the amplifier and the distance was adjusted to obtain maximum directivity, which occurs for spacings of odd multiples of a quarter wavelength [9]. A spacing of $\sim 3\lambda/4$ was found to produce the best gain, rather than $\lambda/4$. This is due to the fact that the antenna input impedance (and hence the match to the amplifier) is affected by the presence of the mirror. This argument was confirmed by measuring the input impedance versus mirror separation using HP 8720 Network Analyzer. Since the impedance is not significantly perturbed for a spacing of $\sim 3\lambda/4$, the ground plane has little effect on the Q factor of this circuit. Furthermore, the Q factor is not strongly influenced by the substrate because it is electrically thin.

Two different techniques were used to characterize the amplifier cell. For the transmission measurement, the technique described in [1]–[3] was used, except that no polarizing elements were required. A simple far-field reflectometer [12] was used to characterize the single cell as a reflection amplifier. Both results are shown in Fig. 2, where the effective isotropic power gain (EIPG) is the quantity displayed. The EIPG is the only directly measureable quantity, defined as $G_{FSd}G_{FSa}G_A$, where $G_A$is the gain of amplifier and $G_{FSa}$ and $G_{FSd}$ are the directional gains of the folded-slot antenna on the air and dielectric sides, respectively. For the transmission measurement, the EIPG is shown both with the device biased on and off. The EIPG in this case is around 11 dB at 4.3 GHz with 3-dB bandwidth of 400MHz or ~10%. Since the substrate is electrically thin, the folded-slot antenna will radiate approximately the same amount of power to both air and dielectric sides. This implies that $G_{FSa}$ and $G_{FSd}$ are nearly the same. This value of $G_{FS}$ is not known exactly, but should be approximately the same as that of a half-wave dipole, which is 1.6 [9] or 2.2 dB. This implies an amplifier gain of 6.6 dB, which is close to the expected result. For the reflection amplifier, the EIPG is significantly higher because the directivity of the antenna is increased by the mirror. When the mirror is taken into account [9], $G_{FS} \simeq 6$ or 7.7 dB, which implies an amplifier gain of 5.6 dB, again close to the expected 6 dB. Note that the gain curves for both transmission and reflection modes have similar frequency dependence. The reflection measurement used a chopping technique [12], where the device is periodically switched on and off, and the signals were detected with a lock-in amplifier. Therefore, the reflection gain is actually the difference between the biased and unbiased measurements.

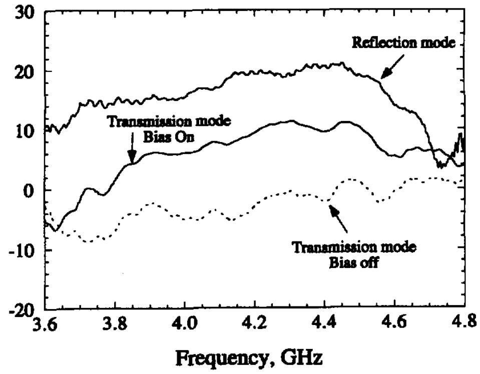

Fig. 2. Measured effective isotropic power gain of the single amplifier cell in both the reflection mode (mirror $3\lambda/4$ behind the cell) and transmission mode. The reflection mode has a higher EIPG due to the increased directivity.

A photograph of the amplifier array is shown in Fig. 3. Since the gain curves for both reflection and transmission proved to be similar for the single cell, only a transmission measurement was made for the array, which is somewhat easier experimentally. The result is shown in Fig. 4. The EIPG in this case is 32 dB at 4.24 GHz with 8% fractional bandwidth. To estimate the actual power gain we again use the half-wave dipole model and incorporate the 4×4 array factor to find the overall array directivity, $G_{AF}$, given by [9]

$$G_{AF} = \frac{4\pi}{\int_0^{2\pi}\int_0^{\pi}[E(\theta,\phi)]^2 \sin\theta d\theta d\phi} \tag{2}$$

where the array factor, $F(\theta,\phi)$, and the element pattern, $E(\theta,\phi)$, are given by

$$F(\theta,\phi) = \left\{\frac{1}{M}\frac{\sin(\frac{M}{2}kd_x\sin\theta\cos\phi)}{\sin(\frac{1}{2}kd_x\sin\theta\cos\phi)}\right\} \cdot \left\{\frac{1}{N}\frac{\sin(\frac{N}{2}kd_y\sin\theta\sin\phi)}{\sin(\frac{1}{2}kd_y\sin\theta\sin\phi)}\right\} \tag{3}$$

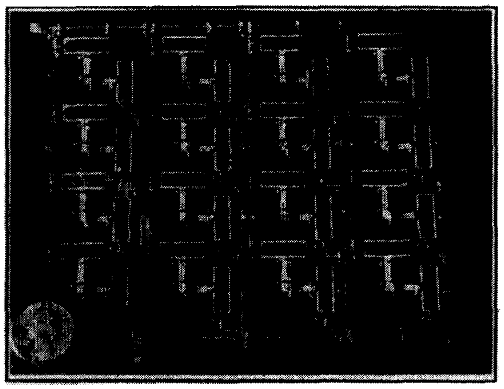

Fig. 3. Photograph of the amplifier array.

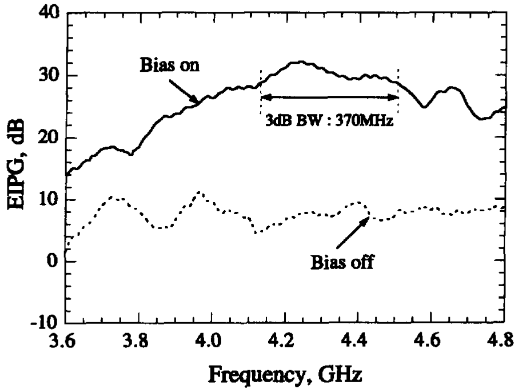

Fig. 4. Measured effective isotropic power gain of the amplifier array in the transmission mode. The array has a directivity of approximately 13 dB.

$$E(\theta,\phi) = \frac{1}{\sqrt{1 - sin(\theta)^2 \sin(\phi)^2}} \cdot \left[\cos(k\frac{1}{2}\sin\theta\sin\phi) - \cos(k\frac{1}{2})\right] \qquad (4)$$

$E(\theta,\phi)$ in (4) is the electric field distribution of a y-directed half-wave dipole of length l; $d_x$ and $d_y$ are the antenna spacings, and $M$ and $N$ are the element numbers in x and y directions, respectively. In our case, $d_x = d_y = \lambda_0/2$, and both M=N=4. Using (2)–(4), $G_{AF}$ is approximately equal to 22 or 13.5 dB. This implies that the average gain of each amplifier in the array is 5 dB, a value consistent with our previous results and expected variations from circuit to circuit.

The dimensions of each cell varied from over the array as a result of difficulties in spinning photoresist and subsequent UV exposure over such a large area, which may explain the smaller gain and bandwidth of the array.

## IV. CONCLUSION

A quasi-optical amplifier cell and amplifier array have been developed that show improved bandwidth as a result of using folded-slot antennas. The circuits are fabricated on one side of substrate without any connection to the back side, an advantage for monolithic array fabrication. A rigorous analysis of folded-slot antenna is planned in order to accurately predict the input impedance and resonant frequencies for better amplifier design.

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