Multi-Slot 50-Ω Antennas for Quasi-Optical Circuits

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***Abstract*—CPW-fed multiple-slot antennas have been developed for active arrays and integrated antennas. This letter describes how the antenna can be engineered for a self-resonant 50-Ω input impedance for a various substrate parameters, and the concepts are verified using a three-slot antenna on $\epsilon_r = 2.2$ substrate and a five-slot antenna on $\epsilon_r = 9.8$ substrate. These antennas have been integrated directly with commercial MMIC gain block chips without any matching networks to create a quasi-optical amplifier array.**

I. Introduction

Quasi-optical solid-state power combining offers a possible solution for efficient power generation and amplification in millimeter-wave range. The idea is to coherently combine the power from many devices in free space, in which the loss is extremely small compared to that in conventional circuits. The energy is radiated to free space by antennas which are coupled to devices through matching networks. The antennas present difficult challenges to the designer: they should have a good radiation efficiency on high-ϵ_r material; they should have a large bandwidth; and they must be easily integrated and impedance-matched to the active circuitry. In this letter we describe a compact variation of the folded-slot antenna, which exhibits a relatively wide bandwidth and an easily engineered input impedance. The antenna uses multiple parasitic slots, and is integrated most easily with coplanar waveguide circuits. As an example of the potential of this structure, we present two designs which exhibit a self-resonant 50-Ω input impedance. One of these designs is integrated directly with a commercial HBT gain block, without any external matching networks required, to produce a low cost quasi-optical amplifier array.

II. Impedance Scaling with Multiple Slots

CPW-fed folded-slot antennas have been suggested as the radiating elements for quasi-optical system due to their simplicity and easy integration with three-terminal devices [1]–[3]. An amplifier array using these antennas [4] has demonstrated a factor of 10 improvement in bandwidth compared to a previously reported amplifier based on patch antennas [5]. In terms of practical circuit designs for quasi-optical systems, it would be useful if the bandwidth and input impedance of the antenna can be adjusted simultaneously without changing the resonant frequency. This requires more degrees of freedom in the antenna layout. It is well known [6] that the input impedance of N-element dipole antenna is given by $Z_{in,N} = N^2 Z_{\mathrm{dipole}}$, where Z_{dipole} is the input impedance of an ordinary half-wave dipole (≈ 70 Ω). Using Babinet's principle [6], an N-element slot antenna would then have an input impedance given by

$$Z_{in,N} = \frac{Z_{\mathrm{slot}}}{N^2} \tag{1}$$

where Z_{slot} is the input impedance of a single slot antenna (≈ 500 Ω in free space). The use of additional slots allows us to "engineer" the impedance of the antenna over a wide range. Obviously the argument will no longer be true if N is too large; there is a limit to the number of slots that can be added while still satisfying (1). Nevertheless, we have been able to vary the impedance by up to a factor of 25 using this technique.

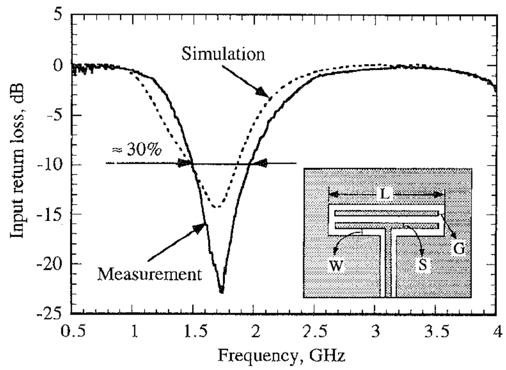

Fig. 1. The calculated and measured frequency response of a triple-slot antenna on 0.813-mm Duroid 5880 ($\epsilon_r = 2.2$). The −10-dB return loss bandwidth is approximately 30%.

A folded-slot antenna on Duroid 5880 with thickness of 0.813 mm and $\epsilon_r = 2.2$ has been analyzed experimentally and theoretically by FDTD technique [3]. This type of simulation accounts rigorously for surface wave effects and the feed discontinuity. The result shows that the electric fields in all slots are in phase which is the necessary condition for impedance scaling. The measured input impedance is 118 Ω at 1.68 GHz. Using the scaling arguments presented above suggests that addition of a third slot (a triple-slot antenna) would produce an input impedance of around 50 Ω for this particular choice of substrate. A triple-slot antenna was fabricated to test the concept, with a length of $L = 78$ mm, a slot width of $W = 2$ mm, and a slot separation of $S = 2$ mm. The measurement was performed on an HP 8720 network analyzer, and the calculated and measured frequency response is shown in Fig. 1. The agreement between simulation and measurement is quite good. The measured input impedance is ≈ 60 Ω at 1.66 GHz, which is obviously close to what was expected on the basis of our simple arguments. The bandwidth at −10-dB return loss is close to 30%.

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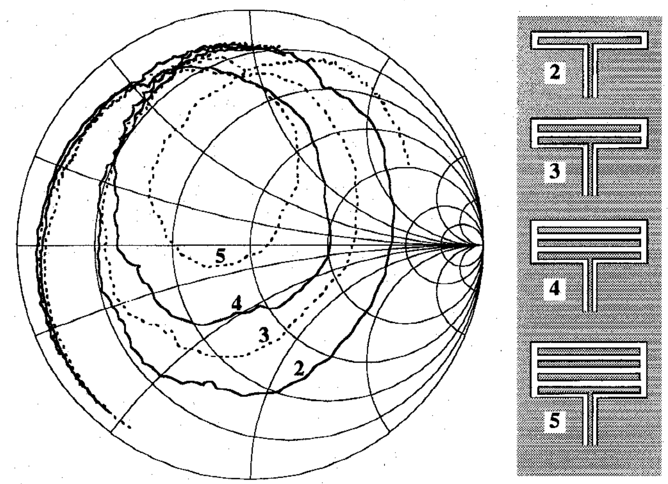

Fig. 2. Demonstration of the impedance scaling with the number of the slots for the 0.635 mm Alumina ($\epsilon_r = 9.8$) substrate for resonant frequencies around 10 GHz. Note that the resonant frequencies of these antennas are about the same, $\approx$ 10.5 GHz.

The idea of impedance scaling was also confirmed on a higher dielectric constant material. The input impedance of a 10 GHz folded-slot on Alumina ($\epsilon_r = 9.8$) with thickness of 0.635 mm is $\approx 300\ \Omega$ from FDTD simulation [3]. This implies that a 50-Ω impedance can be obtained if five slots are used. A five-slot antenna with $L = 7.2$ mm, $W = 0.4$ mm, and $S = 0.2$ mm, was fabricated and measured, using an HP 8510B with a Cascade Microtech wafer probing setup. This antenna resonates at 10.5 GHz with an input impedance equal to 58 Ω. The -10-dB return loss bandwidth is approximately 10%, which is smaller, due to higher dielectric constant, compared with the example above on low dielectric constant substrate. To demonstrate the influence of additional slots on the input impedance, two-, three-, and four-slot antennas on the same Alumina substrate were fabricated and measured. The results are shown in Fig. 2 along with data for the five slot antenna. The impedance is scaled in close agreement to (1) as the number of slots increases. The resonant frequencies of these antennas are about the same, $\approx$10.5 GHz, which is primarily determined by the length of the slot, L, and is not affected significantly by the number of slots.

III. Quasi-Optical Amplifier Cell

The 50-Ω antenna structure allows us to directly integrate commercial MMIC chips that are designed for a 50-Ω input/output impedance. To explore this idea, we constructed a quasi-optical amplifier cell by bonding a typical MMIC amplifier block between two five-slot antennas (described above), without any external matching networks. A 10-dB Rockwell HBT gain block was tested. This device was first characterized using HB 8510B with a Cascade wafer probing setup and has approximately 10-dB gain around 10 GHz, with a unity-gain cutoff of approximately 18 GHz. The amplifier cell was then measured in a oversized square waveguide using a HP 8720 network analyzer. This measurement setup allows us to obtain the gain of this amplifier cell *directly,* unlike previous measurements [4] which rely on the Friis transmission equation [6]. Two waveguide transitions were machined to make a smooth taper from standard X-band waveguide to a one inch square aperture. The one-inch square middle section allows the propagation of signals with both vertical and horizontal polarizations, which is used to isolate the input and output signals. Note that a polarizer was used in front of the amplifier cell in order to direct the output radiation in the forward direction; in addition, this provides some tuning for better output match. Fig. 3 shows the gain curves from the HP 8720. The 3-dB bandwidth is $\approx$ 4% with peak gain equal to 8 dB. The narrower bandwidth of this circuit compared to that of the single antenna measurement is expected, due to the use of two antennas and the frequency-dependent gain of the amplifier in this frequency range. Larger bandwidth could be obtained with additional matching circuitry if needed, and also by optimizing the antenna, which is discussed in [3].

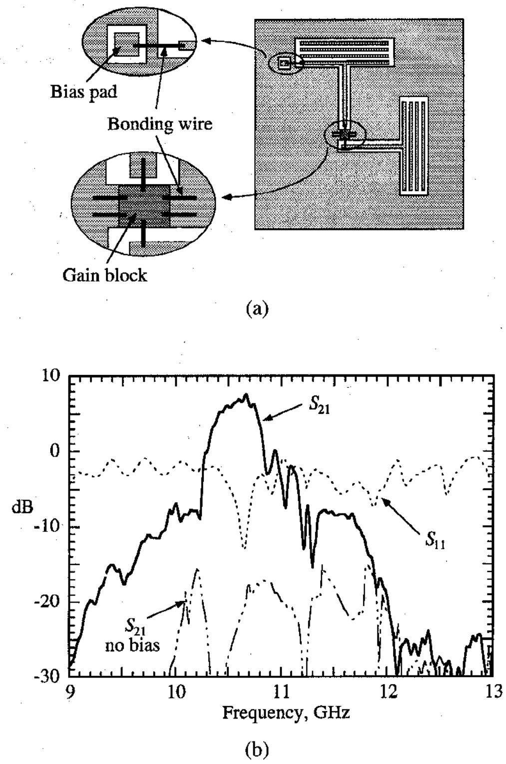

Fig. 3. (a) Picture of the amplifier cell with direct integration of 50-Ω five-slot antennas and a commercial HBT gain block MMIC chip. The amplifier cell is fabricated on a 2.54 cm × 2.54 cm Alumina substrate and the dimensions of the antennas are given in the paper. (b) The gain curve (direct measurement) of this amplifier cell in a square waveguide, with and without dc bias.

IV. Conclusion

Two 50-Ω planar multiple-slot antennas were presented in this paper. These CPW-fed antennas are suitable choice as the radiating elements for quasi-optical system because of their relatively wider bandwidth compared to other resonant antennas. They are also preferable for MMIC's since no backside processing (via holes) are required for integration with devices; more importantly, they can be integrated directly with off-the shelf MMIC's, which is demonstrated by a quasi-optical amplifier cell using five-slot antennas and a HBT gain block.

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