Quasi-Optical Power Amplifier Using TEM Waveguide Concept

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***Abstract* — A new E-plane quasi-optical waveguide power amplifier with an innovative low-loss integrated transition array of finline and microstrip is presented, which employs a concept of TEM mode waveguide. This TEM waveguide was proposed on a uniplanar periodic patterned surface or usually called uniplanar compact photonic bandgap (UC-PBG) structure. Our Ku-band back-to-back transition array demonstrates a return loss better than –17.5 dB and an insertion loss better than –0.65 dB. The TEM waveguide is found to have a 1-GHz bandwidth centered at 14.5 GHz. The use of such a frequency-selective surface has showed that one could implement more power cards inside this TEM waveguide. The space power combiner is used to combine the output powers of twelve 20 mW MMIC amplifier chips. The power module yields a 21.08 dBm output power including the loss of transition and a combining efficiency of 89% is observed in this work.**

I. Introduction

Power amplifier (PA) is crucial in the design of wireless communications and in particular for transmitter, which generally has good characteristics available now at low microwave frequencies. Nevertheless, they are still limited in power and difficult to design at high microwave frequencies and millimeter-wave frequencies. This is why it has stimulated a special interest in finding other alternative solutions.

A well-justified potential technique is the use of a spatial power combining technique [1], for example, the tray-type of architecture. A remarkable advantage of using such a scheme is that the insertion loss usually does not increase by increasing the number of amplifier elements. This can be very attractive for the design and application of high power system in which a large number of power devices have to be combined. This is in fact a typical scenario related to the system implementation at high microwave and millimeter-wave frequencies.

A number of works have been carried out to solve this problem in particular those reported in [2-5]. Broadband spatial power combining technique using dense finline arrays was proposed with output power ranging from 20 to 120 watts over X-band, showing promising features. This technique, however, has some problems, for example, the limitation of the number of active device due to the non-uniform TE_{10} modal electric field across the waveguide. To increase the number of power card in the waveguide, a technique has recently been developed [6], in which an oversized combiner was designed to accommodate more trays. In this case, both TE_{10} and TE_{20} modes can propagate at a particular operating frequency. Nevertheless, by using a symmetric loading of the structure, modes with odd symmetry such as TE_{20} mode can effectively be suppressed.

Recently, several periodically patterned surfaces called photonic bandgap (PBG) or electromagnetic bandgap structures have been demonstrated to be useful in enhancing performance of microwave circuits. A uniplanar compact PBG (UC-PBG) structure has also been presented for various applications [7-8], which has some interesting properties, namely, compact size, low loss, and broad stopband. In [9], a novel TEM waveguide using this periodic structure was realized. This structure realizes a magnetic surface in the stopband and it is used to construct the two bilateral waveguide walls so to provide magnetic boundary conditions. A relatively uniform field distribution along the cross section has been obtained.

In this work, we propose a novel quasi-optical amplifier in a TEM waveguide. In Section II, characteristics and the realization of a perfect magnetic conductor (PMC) surface are presented. In Section III, the design of tapered finline arrays, and more importantly the design of a new transition between finline and microstrip are presented. The same transition can be used to excite the non-conventional TEM waveguide. Section IV shows the fabrication and measurement aspects of the power amplifier with the integration of the different components discussed in the previous section.

II. Design and Measurement of the Periodically Patterned Structure

The UC-PBG surface of interest and a measurement technique used to characterize it are described in Fig. 1. This structure is a two-dimensional periodic lattice patterned on a conductor dielectric substrate, which is in fact a frequency-selective surface. The surface impedance of the proposed structure is frequency sensitive since it

0-7803-6540-2/01/$10.00 (C) 2001 IEEE

actually forms a distributed *LC* network with specific resonant frequencies. At those frequencies, the periodic loading becomes an open circuit; an equivalent magnetic surface is thus created. This phenomenon can be examined in experiment by measuring the coefficient of reflection as illustrated in Fig. 1. The phase of the reflection coefficient of a PMC plane should exhibit a difference of 180^o compared to that of a perfect electric conductor (PEC) plane.

Two types of scatter used in this experiment are an intact copper sheet (PEC) and a UC-PBG surface, both fabricated on a conductor-backed substrate (Duroid 6010) with dielectric constant of 10.2 and thickness of 25 mil. Fig. 2 shows the phase difference in reflection coefficient between the PGB and PEC surfaces. As can be seen, an 180^o phase difference occurs around 14.4 GHz, indicating that a magnetic surface has successfully been realized. A theoretical simulation based on HFSS package shows a close agreement with an error of 3%, which might be caused by the lossless dielectric consideration of HFSS.

Fig. 3 illustrates a second measurement taken on the UC-PBG surface. One can notice that in the area where the surface becomes magnetic, the waveguide behaves like a stopband filter over a frequency band of approximately 1 GHz. It is thus necessary to design a new transition to be able to excite a TEM mode in the waveguide that will be discussed in the next section.

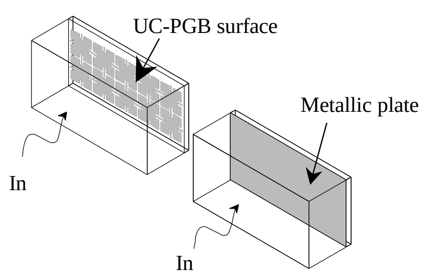

Fig. 1. Pattern of the UC-PGB and measurement techniques.

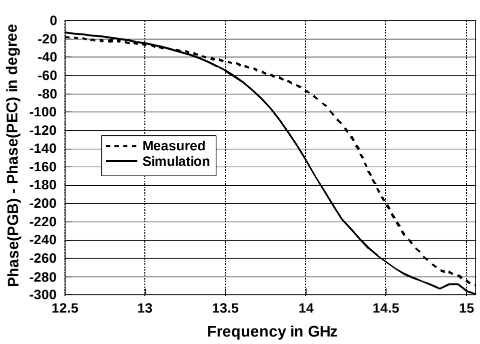

Fig. 2. Measured and simulated results of phase differences in reflection coefficients between the PGB and metallic plate.

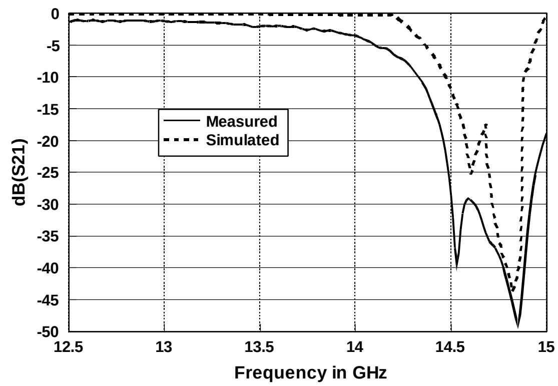

Fig. 3. Measured S_{21} in the waveguide using the UC-PGB surface.

III. Design of Space Power Combiner in Waveguide

The topology of our broadband power combiner is based on the work done in [2]. This power combiner consists of a 2D array of finline antennas, which consist of tapered slotline sections with a transition to microstrip as illustrated in Fig. 4. These cards are mounted onto a small metal test fixture, for both mechanical and heat removal, and inserted in the standard Ku-band waveguide Receiving and transmitting signals from and to the waveguide, the finline antenna sections also serve as impedance transformers, providing matched load to the source. The design work is based on the theory of small reflection and analytical results of Klopfenstein tapers as detailed in [10]. HFSS is used to analyze the finline array structure to obtain the relation between the physical dimensions of the structure as well as its impedance and propagation constant. The finline is fabricated on a Duroid substrate with a dielectric constant of 2.22 and a thickness of 10 mil.

For the transition between finline and microstrip, our design is inspired from work carried out on the transition between microstrip and slotline. The transition considered here is sketched in Fig. 5. Due to our current fabrication restriction, the smallest gap that we can obtain for the finline is 6 mil, which corresponds to about 117 Ohm impedance line. The dimensions are chosen for a center frequency of about 15.25 GHz. The microstrip width and stub length are respectively selected with W_m = 5.7 mil and l_m = 150.9 mil which correspond to an impedance of 116 Ohm. For the finline, the width is W_f = 6 mil and the stub length is L_f = 172.8 mil. In order to transform the impedance Z_m to the 50 Ohm impedance, a quarter-wavelength line with a characteristic impedance of 76.2 Ohm is used. The dimension of this line are W = 14.9 mil and l = 143.1 mil. Fig. 6 gives the sketch of the circuit of test. The measured return loss and the insertion loss of the back-to-back transition are showed in Fig. 7. The return loss is better than –17.5 dB for the entire waveguide band. The insertion loss is not higher than 0.65 dB. It is worth noting that theoretically there is no upper limit for the bandwidth of the gradual taper, and therefore the bandwidth is actually limited by the choice of waveguide.

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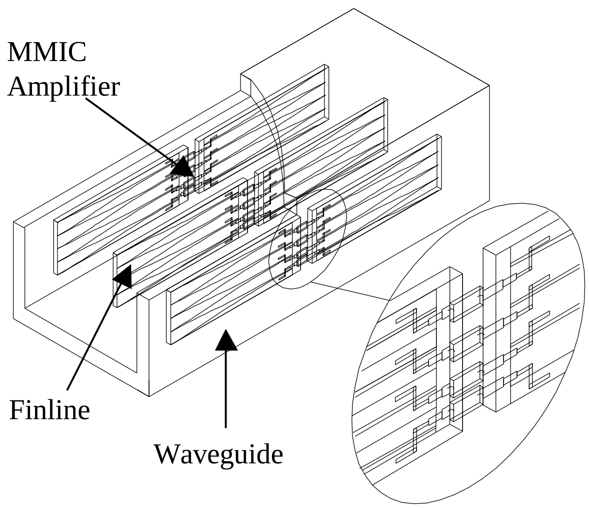


Fig. 4. Topology of spatial combiner

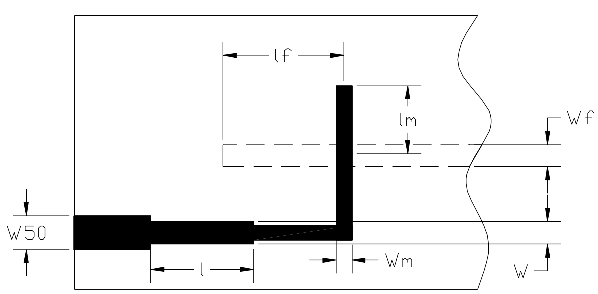


Fig. 5. Transition between finline and microstrip

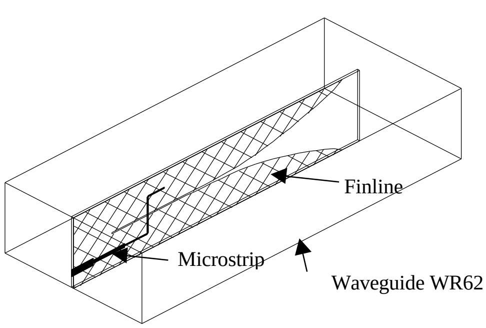
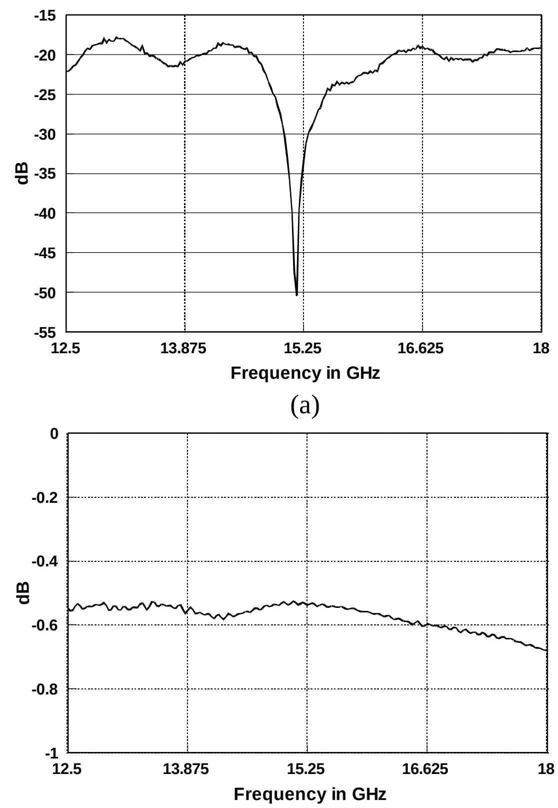


Fig. 6. Measured test circuit.



(b)

Fig. 7. Measurement of the transition between finline and microstrip. (a) Return loss. (b) Insertion loss

IV. MEASUREMENT OF THE PROPOSED AMPLIFIER

To excite the TEM mode in the waveguide, the same transition between finline and microstrip were used as illustrated in Fig. 6. The topology of the finline is recomputed to take account of the new profile of impedance of the TEM waveguide. A broadband response with a low return loss (<-16 dB) has been obtained.

To better understand the effect of integration of the UC-PGB surfaces along the bilateral walls of the waveguide, two measurements are carried out. The first measurement is done by using six cards inside the waveguide without the UC-PGB surfaces whereas the second one is carried out by using the same structure but by integrating the UC-PGB surfaces. Each card supports two low-cost amplifier cells whose output power are 20 mW. The distance between the cards is 80 mil. Fig. 8 illustrates measurement results of the output power with respect to the input power. This measurement is taken at

14.75 GHz to take account of the operable range of the UC-PGB surface. It is noticed that the output power increased by 1.5 dBm in the case of the use of the UC-PGB surfaces. This can easily be explained by the fact that due to a more uniform distribution of the field, the amplifier cells on the power cards are compressed or saturated almost simultaneously whereas in the first measurement the amplifier cells that are more centrally located starts to get compressed or saturated before the other cells that are located elsewhere in the waveguide.

The efficiency of the power combining system is known as the efficiency of the amplifier cells multiplied by the loss of the passive combiner when the gain of the amplifier cells becomes very large. The combiner loss can be calculated by the following equation using S-parameters of a through line measurement.

$$LF \approx \sqrt{\frac{|S_{21}|^2}{1 - |S_{11}|^2}}$$

Our average combining loss of 0.65 dB indicates that a combining efficiency better than 89% can readily be achieved.

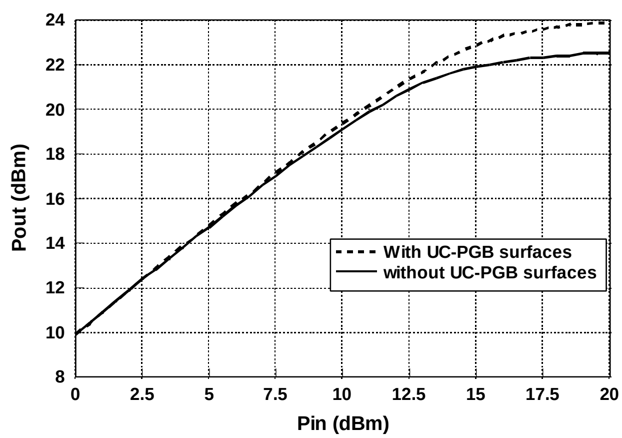


Fig. 8. Measured output power with UC-PGB and without UC-PGB surfaces at 14.75 GHz.

V. Conclusion

This paper has demonstrated that a new quasi-optical power combiner and high-efficient power amplifier can be designed in a TEM waveguide. The use of periodically patterned planar structures or UC-PGB surfaces allows obtaining a 1.5 dBm gain in power as indicated by our measurements. This can especially become very significant when the output power becomes high, as well as high microwave frequency or millimeter-wave frequency power amplifiers are required.

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