Two-Dimensional Quasi-Optical Power Combining System Performance and Component Design

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Abstract. In this paper, the design of a 2D quasi-optical power combining structure is presented. Convex and concave phase transformers were used in the system comparing their scattering losses. The amplifier array is placed underneath the dielectric slab to reduce insertion loss and can also generate beam scanning by tuning the input signal frequency.

1. Introduction

Recent advances in the entirely new technology of two-dimensional quasi-optical power combining promise significant progress in bringing the advantages of solid state monolithic technology to moderate and high power millimeter-wave applications. A major characteristic of the conventional quasi-optical circuits is the use of three-dimensional free space for the power combining. We have built on this concept to develop a quasi-optical system which combines power in two dimensions. In [1,2], we have demonstrated power combining in a dielectric substrate using amplifier and oscillator arrays. Furthermore, our experiments indicate that the 2D geometry can lead to circuits which are less sensitive to instabilities and are easier to optimize for efficiency as well as being smaller and lighter.

A 2D quasi-optical power combining amplifier stage, shown in Fig. 1, confines a Gaussian beam-mode within the dielectric where the signal is focused by a lens (a phase transformer) to produce a Gaussian beam-mode. The signal is amplified by an amplifier array that is placed underneath the dielectric and centered in the Gaussian beam for optimum performance. In our previous work [2] the amplifier array was located on the top surface of the dielectric where it suppressed the beam-mode by about 5 dB. In this paper we present results for the amplifier stage including mode coupling, insertion loss of amplifiers with different substrates, passive system gain, amplifier gain, field profiles, and power in versus power out. For these results the amplifier stage includes both concave and convex lenses. Furthermore, the measured field profile indicates that the beam-mode perturbation reduces to 1.5 dB. Also, concave lenses result in less scattering loss than convex lenses.

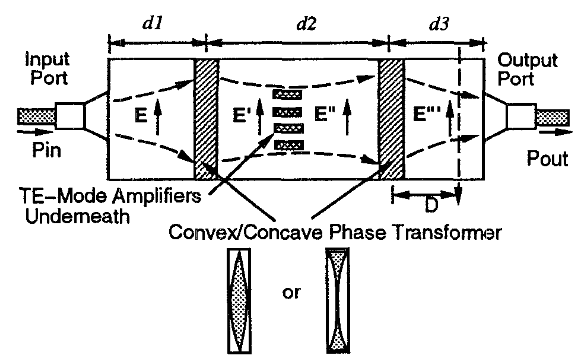

Figure 1: The DSBW system with amplifiers underneath the slab. ($d1 = 12cm$, $d2 = 28cm$, $d3 = 16cm$, $D = 12cm$)

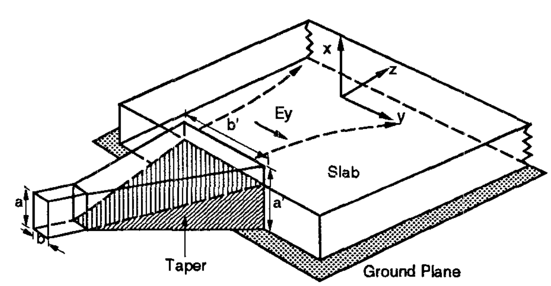

Figure 2: Energy transmitting from waveguide to the DSBW.

2. System and Component Design

The 2D quasi-optical power combining system in Fig. 1 includes, radiating and receiving horns, a di-

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electric slab beam-mode waveguide (DSBW) [3], convex/concave phase transformers, and an amplifier array placed under the dielectric slab. In order to launch more energy into the DSBW system, tapered horns are added into the system as shown in Fig. 2. The taper was selected to be 12.5 cm long so that the characteristic impedance of the TE mode varies slowly, and the reflection coefficient becomes very small. The reflection in the feeding neck can be calculated using [4]

$$\Gamma_{TE} = \int_0^L e^{-j\beta_z z} \frac{1}{2\beta_z} \frac{d\beta_z}{dz} dz$$

where β_z is the propagation constant inside the taper with $L = 12.5$ cm. The β_z can be obtained by solving the characteristic equation for the partially-loaded waveguide [5]. The calculated reflection is lower than 0.007 when the operating frequency is higher than 7 GHz. When only the TE_{10} mode is excited in the feeding waveguide, multiple TE_{0m} modes are coupled from the horn aperture to the DSBW. The TE_{10} mode in the horn aperture is constant in the y-direction, so $TE_{10} \propto \sqcap(y/b')$. Expanding $\sqcap(y/b')$ into

$$\sqcap\left(\frac{y}{b'}\right) = \sum_{m=0}^{\infty} a_m He_m \left(\frac{2y}{W_{o,1}}\right) e^{-y^2/W_{o,1}^2}$$

the relative amplitude, a_m, for each coupled TE_{0m} mode in the slab can be obtained. He_m is the Gaussian-Hermite function, and $W_{o,1} = 9$ cm is the beam width of all TE_{0m} modes. The calculated data shows that only even a_m exist, and $a_m \rightarrow 0$ when $m > 4$. This means that a single TE_{10} form input mainly couples energy into the TE_{00}, TE_{02} and TE_{04} Gaussian-Hermite modes inside the slab. The total coupled fields in the DSBW are then composed of these three modes. The theoretical field is calculated with ($a_0 = 0.736$, $a_2 = -0.253$, and $a_4 = 0.04$). The calculated pattern matches the measured pattern, and is shown in Fig. 3.

Amplifiers placed on top of the slab highly perturb and suppress the beam-mode by about 5 dB (see [2]). In an effort to reduce this effect the amplifier array was moved underneath. However in [2], the amplifiers were built on substrate RT/Duroid 5870 (low dielectric constant $\epsilon_r = 2.33$), and caused about 5 dB insertion loss when they were located underneath (see Fig.4). Alternatively, building the amplifier unit on RT/Duroid 6010 (high dielectric constant $\epsilon_r = 10.5$) reduced the discontinuity between the amplifier substrate and ground plane, and the loss became only 1.5 dB as shown in Fig. 4. When the guided waves travel through the amplifiers, part of the waves are amplified by the amplifiers, and the rest travel through the waveguide as shown in Fig. 5. These two waves E_a and E_{th} combine to produce the output wave E_{out}.

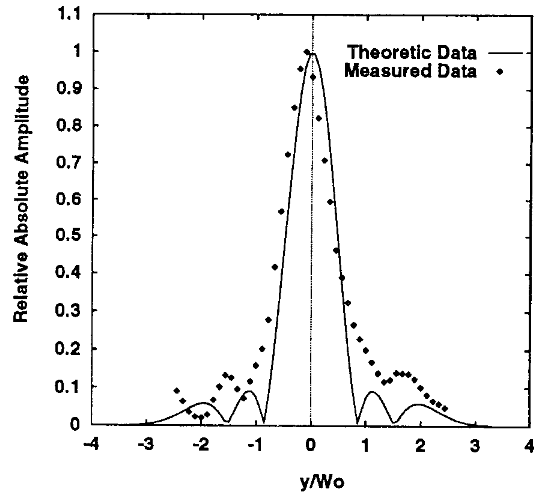

Figure 3: Calculated and measured coupling mode in the DSBW.

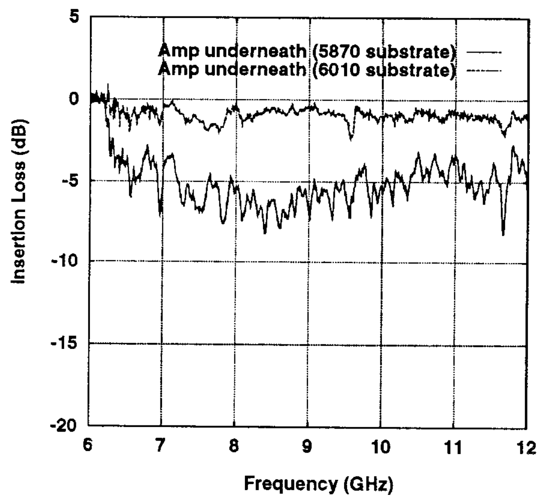

Figure 4: Insertion loss for an amplifier underneath the slab ($\epsilon_r = 2.33$ for Duroid 5870; $\epsilon_r = 10.5$ for Duroid 6010).

3. System and Component Performance

In this system design, convex/concave-lens phase transformers are applied to reiterate beam-modes through the DSBW. The convex lenses are made of Macor ($\epsilon_r = 5.9$) while the concave lenses are made using an air gap between in the DSBW. Fig. 6 shows the passive system gains for the system without the amplifier array. This passive gain indicates the concave lenses cause less scattering loss than the convex lenses when the beam-modes pass through them. Another advantage of using a concave-lens phase transformer is that it is more appropriate to the design of the 2D

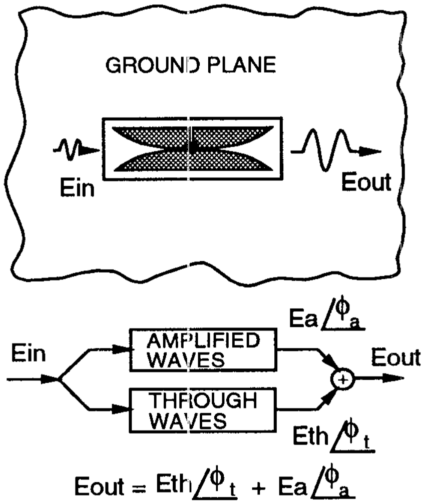

Figure 5: Wave model for amplifier array underneath the slab.

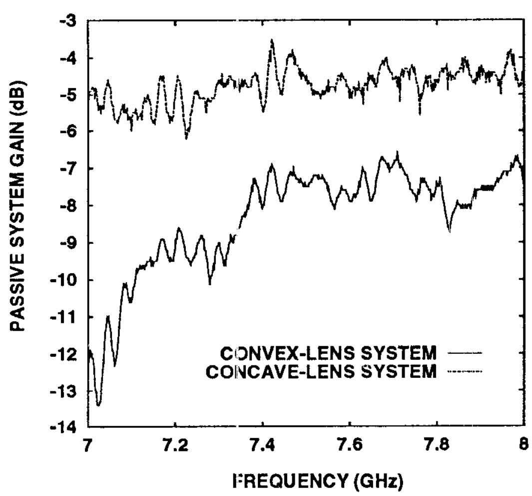

Figure 6: Passive system gain for convex/concave-lens system.

power-combining system in MMIC. Fig. 7 shows P_{in} and P_{out} for the system operating at 7.24 GHz. The active system gain, $P_{in} - P_{out}$, is about 11 dB when $P_{in} < -15$ dBm. Note that the active system gain becomes smaller when $P_{in} > -15$ dBm. This is because the amplifiers are working in the saturation region, and the amplified waves E_a are weaker than the through waves E_{th}. Therefore, the through waves E_{th} dominate the output waves E_{out} at high input power levels.

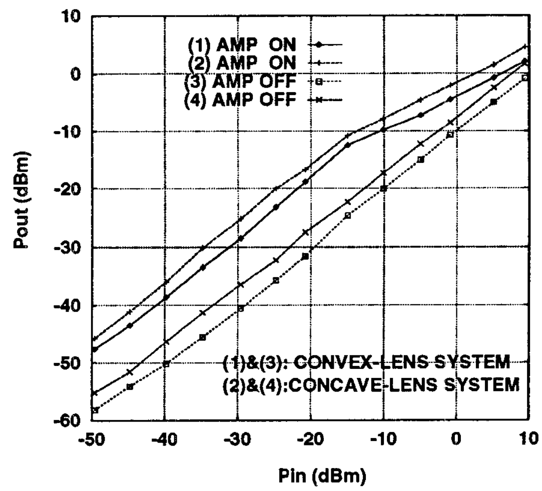

Figure 7: P_{in} and P_{out} of the convex/concave slab system.

The insertion loss and gain of the amplifier array underneath the slab are shown in Fig. 8. The highest gain is 19.5 dB at 7.228 GHz and the insertion loss is about 3.5 dB. The array insertion loss here is still less than the insertion loss for one amplifier built on a low-dielectric-constant substrate (see Fig. 4). This is important information for determining which amplifiers to use. Moreover, there is a zero gain at 7.182 GHz in Fig. 8, and this is because of beam-mode splitting as shown in Fig. 9.

When the input wave operates at 7.182 GHz and 7.228 GHz , the $|E_y|$ patterns measured at the position D =12 cm (see Fig. 1) are shown in Fig. 9 and Fig. 10. In Fig. 10, the field pattern jumps up 15 dB and still keeps the TE_{10} Gaussian-Hermite beam-mode. In Fig. 9, the field pattern splits and almost changes to the TE_{20} Gaussian-Hermite beam-mode. In Lin and Itoh's work [6,7] , they tune the bias to switch modes. In our work, these two figures show that this 2D power combining system can also generate beam scanning into free space by only tuning the input signal frequency. From these two figures, one can find that the input beam-mode is suppressed by 1.5 dB by the amplifier stage at $|Y| < 5$ cm range, and is less than our previous work [2] in which the field is suppressed by 5 dB.

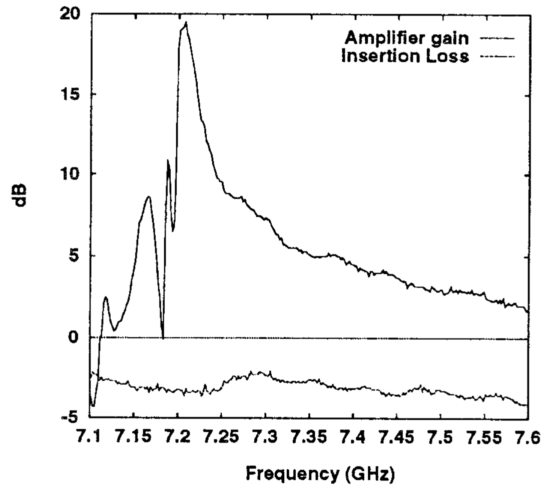

Figure 8: Insertion loss and gain of the amplifier array underneath the slab.

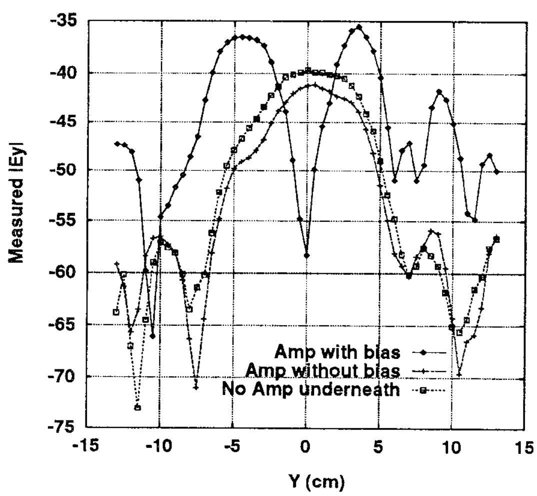

Figure 9: Measured $|E_y|$ at 7.182GHz.

4. Conclusion

In this paper, we presented the design consideration for wave launching, mode coupling between horn and DSBW, and amplifier substrate in a 2D quasi-optical power combining system. Measured data shows that the concave lenses cause less loss and are more appropriate for the MMIC fabrication of the 2D quasi-optical power combining system. An amplifier array located underneath the slab significantly reduces the beam perturbation.

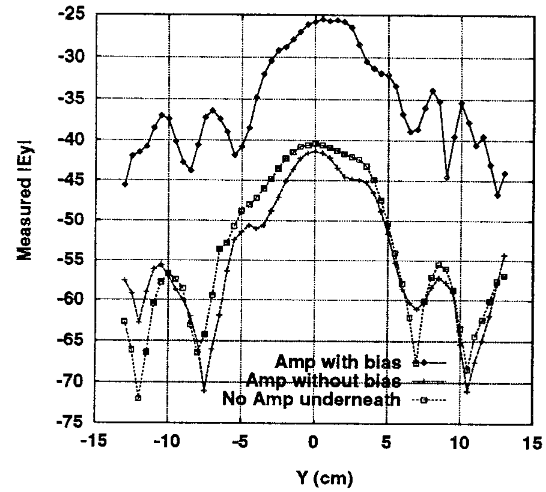

Figure 10: Measured $|E_y|$ at 7.228GHz.

Acknowledgment

This work was supported in part by the U.S. Army Research Office through grant DAAH04-95-1-0536.

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