

## ACTIVE QUASI-OPTICAL COMPONENTS FOR COMMUNICATIONS

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**Abstract.** In this paper we describe a new approach to what we believe are more reliable, less expensive, and more compact front ends for microwave and millimeter-wave communications. This new approach is based on quasi-optical components, i.e. microwave and millimeter-wave systems which use some traditionally optical components. Examples of such components are gratings, lenses, Gaussian-beam systems, mirrors and open resonators. In the last decade, it has been suggested that the powers of a very large number of low-power solid-state devices can be combined in free-space using quasi-optical techniques. Usually, such an active device consists of a printed array loaded with diodes or transistors. The active devices feed radiating elements in the array, and the powers of the individual elements are combined coherently in free space.

### 1. Introduction and background

Many active quasi-optical components have been demonstrated to date: oscillators [1–8], amplifiers [9–13], mixers [14], phase shifters [15,16], multipliers [17], and switches [18]. In this paper, first a number of components

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are described, and then subsystems consisting of several active quasi-optical components are presented.

The most important front-end component of a communication system is the transmit/receive (T/R) module. A quasi-optical transceiver, consisting of a self-oscillating FET mixer, was reported in [19], but this circuit did not incorporate power amplification, low-noise amplification, or modulation functions. Here we describe analysis, design and measurements of the necessary quasi-optical T/R components. We also discuss a way to construct a quasi-optical transceiver from the presented components and present some demonstration results.

Originally developed to address the need for high-power millimeter wave sources [20], quasi-optical circuitry has several advantages for wireless communication applications:

- Millimeter waves offer more bandwidth, and the increased atmospheric attenuation forms a natural cell boundary, making these frequencies ideal for short-range, high-capacity indoor networks for high-speed data or multimedia transmission. The limited output power of millimeter-wave solid-state devices is overcome by spatially power-combining hundreds of low-power devices [1,5]. This allows power levels in the tens of watts range, adequate for terrestrial and satellite communications.
- Quasi-optical active components are compact, light-weight, and amenable to monolithic integration. The antenna is an integral part of the circuit design, which allows for overall system size reduction.
- In a mobile environment where S/N ratios fluctuate wildly due to multipath and shadow-fading, dynamic power control and adaptive beam-steering techniques are needed to obtain energy-efficient systems. Recently, quasi-optical amplifiers with beam-steering and beam-forming capabilities have been demonstrated [12,13].
- The total output power is a result of combining a large number of devices. Hence, the reliability of quasi-optical components is good; a fraction of the devices can fail before the component fails [21,22].

## 2. System components

The results presented here describe components which perform all of the functions that a quasi-optical transceiver requires: signal generation, amplification, reception, modulation and beam control.

Reliable, compact, solid-state oscillators are needed for signal generation and as LOs. In the first planar grid oscillator to demonstrate large-scale power combining [1], the powers of 100 MESFET oscillators were spatially combined to produce an effective radiated power of  $21W$  at  $5GHz$ . In the

grid, all of the devices are biased in parallel. The grid period is much smaller than a free-space wavelength and the devices are tightly coupled, which causes the grid to act as a uniform active sheet, as opposed to a standard antenna array. A mirror is placed in parallel with the grid and the two surfaces form an instable Fabry-Perot cavity. This allows for self-locking and unidirectional radiation. This type of device has demonstrated graceful degradation, as shown in [21,22]. In [7], a full-wave theory for analyzing grid oscillators consisting of arbitrarily shaped metal gratings printed on one or both sides of an arbitrary dielectric was presented. Several successful grid oscillators have been designed with this analysis tool, including C-band oscillators [7], X-band oscillators [12], and stacks of grid oscillators [6]. For example, Fig. 1 shows a grid oscillator designed to operate at  $10.25\text{GHz}$  as a feed for a narrowband free-space lens amplifier. This grid has a rectangular unit cell and an asymmetric metal geometry. It was built with 28 PHEMTs and oscillated exactly at the design frequency [12]. Another example is a millimeter-wave grid oscillator, fabricated and tested in collaboration with TLC Precision Wafer Technology Inc. and Honeywell (Minneapolis). The simulated oscillation frequency using small-signal device parameters is  $31.25\text{GHz}$ , while the 100-PHEMT monolithic grid locked at  $31.1\text{GHz}$  [23].

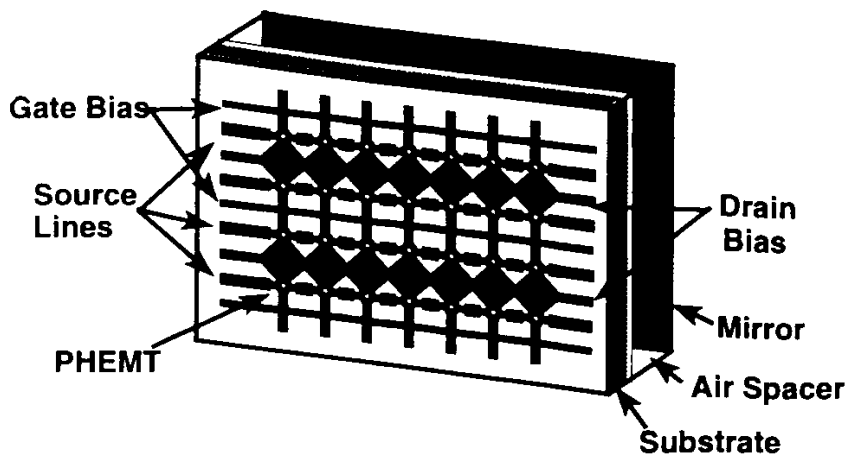


Figure 1. A 10.25-GHz grid oscillator (designed with our full-wave analysis program) operates exactly at the design frequency and is used as a focal-point feed for a lens amplifier combiner [12]. More recently, a theory for analyzing cascaded systems of multi-function

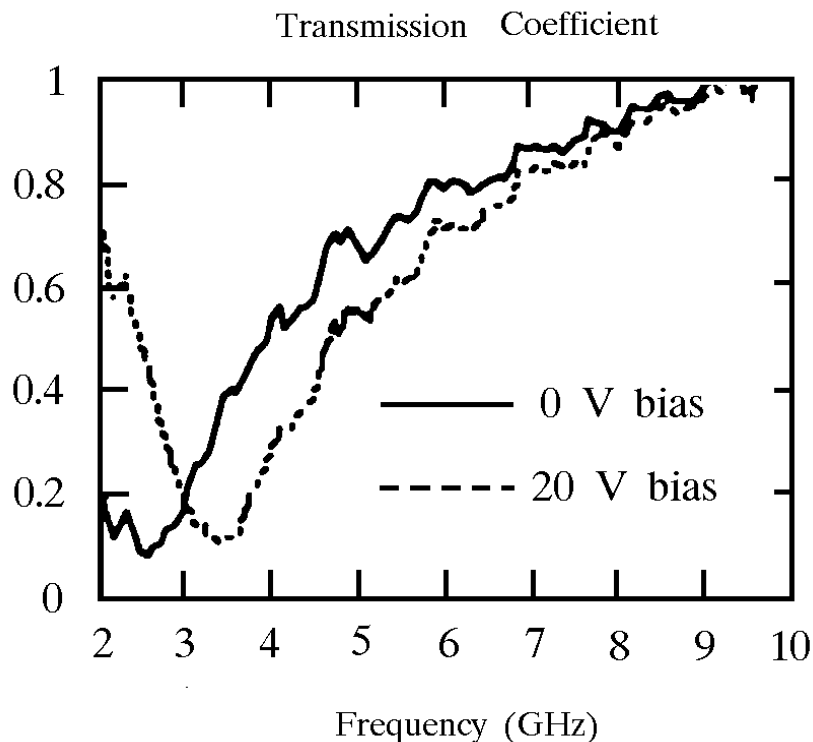


Figure 2. The measured electrical tuning of the resonance of a varactor-loaded tunable FSS shows a 30% bandwidth with very little change in resonance amplitude [25].

grids, including fixed-frequency and tunable filters, and mode-selective grid oscillators was developed [24,25]. Filters, especially those with sharp rolloff characteristics, are essential for communication systems. Tunable filters offer additional system flexibility. A voltage-controlled frequency-selective surface (FSS) was designed using the theory presented in [24]. It consists of a printed grid loaded with varactor diodes. The resonance of this filter tunes in a 30% bandwidth when the bias across the diodes is changed, as shown in Fig. 2. This FSS was placed in front of a 25-PHEMT grid oscillator and allowed the locked frequency to be set at either 4 or 6GHz [25]. The radiation patterns and cross-polarization levels for both frequencies are the same. The ability to selectively choose the carrier frequency is useful for frequency-diversity systems.

Low-loss circular polarizers which can be inserted in the transmission path are useful, as circular polarization has been shown to suppress multipath-delayed waves [26], resulting in improved transmission characteristics. In [25], a linear-to-circular polarization converter was presented which has a  $1.2\text{dB}$  axial ratio with only a 1-dB transmission loss at X-band.

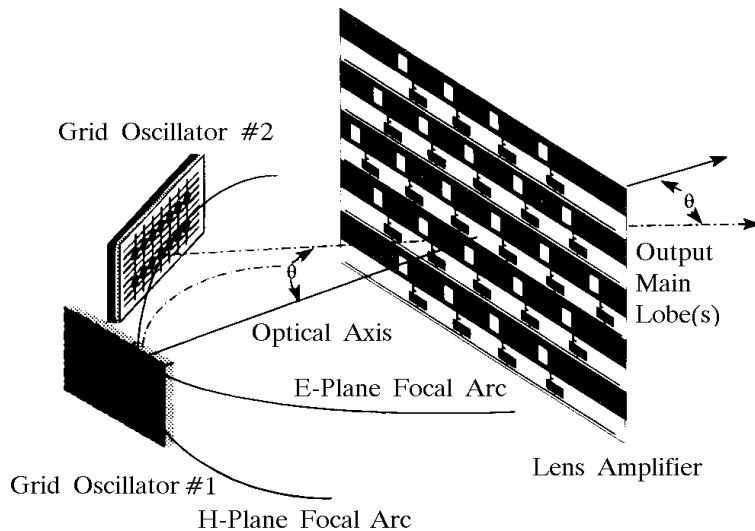


Figure 3. A quasi-optical planar lens amplifier fed by two identical grid oscillator sources positioned along a focal arc of the amplifying lens [13].

High gain, low noise and power amplifiers are necessary parts of every transceiver. A lens amplifier array using patch antennas is shown in Fig. 3. This amplifier demonstrated 8 dB of absolute power gain in a 3% bandwidth at  $9.7\text{ GHz}$  [12]. The input side patches (shown in black) have variable delay lines across the array, allowing for a focal-point near-field feed. This enables efficient input feeding as well as simple transmitter design with the added capability of beam-steering and beam-forming.

In a mobile environment, where signal-to-noise ratios can fluctuate wildly, dynamic power control and adaptive beam-steering techniques can be used to maintain a low bit error rate and reduced sensitivity to multipath and shadow-fading. Beam-steering and beam-forming have been demonstrated with quasi-optical lens amplifiers [12,13]. The lens amplifier in Fig. 3 is fed by two identical grid oscillator sources positioned along a focal arc of the amplifying lens. When the two sources are turned on simultaneously, the

fields are linearly superimposed at the amplifier output to produce a pattern with two distinct beams due to the two respective sources [13]. However, the two sources can also be switched on and off one at a time to produce a fixed number of discrete switchable beams for a steering system. We have measured a  $5 - kHz$  steering speed, limited by the settling time of the oscillator feeds.

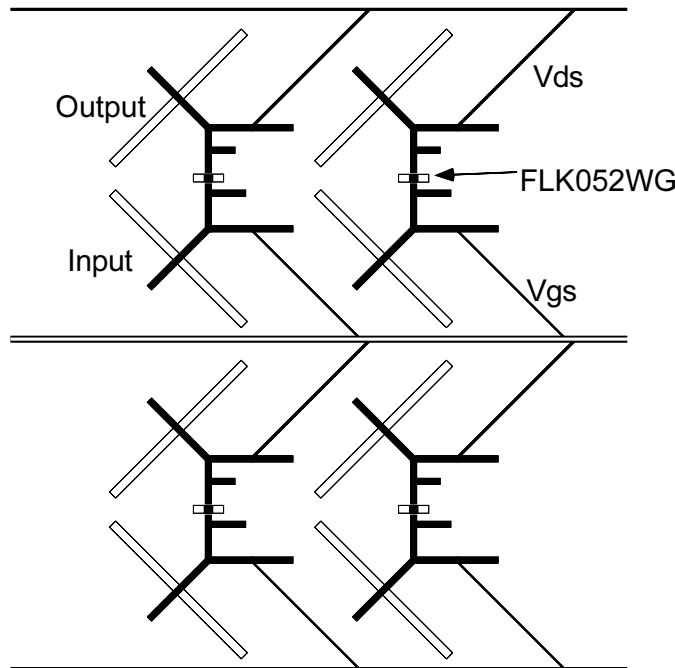


Figure 4. Layout of a plane-wave-fed slot antenna power amplifier. Unfilled rectangles show the positions of the slot antennas on the back of the substrate [27].

High-efficiency quasi-optical amplifiers increase battery lifetime, and reduce overall size and weight due to lower heat-sinking requirements. By increasing the efficiency from 50% to 90%, the dissipated heat power is reduced by a factor of nine for the same amplifier output power. For two-dimensional amplifier antenna arrays, low heat dissipation is especially crucial, since the heat flow is lateral. A high-efficiency power amplifier array using anti-resonant slot antennas, shown in Fig. 4, exhibits 10 dB gain, 2.5W of power with 65% power added efficiency at 5 GHz from only 4 MESFETs [27]. This concept can be extended to millimeter-wave frequencies, as was demonstrated in [28] for a Ka-band amplifier which demonstrated 6 dB of small-signal gain and 1 watt of saturated output power.

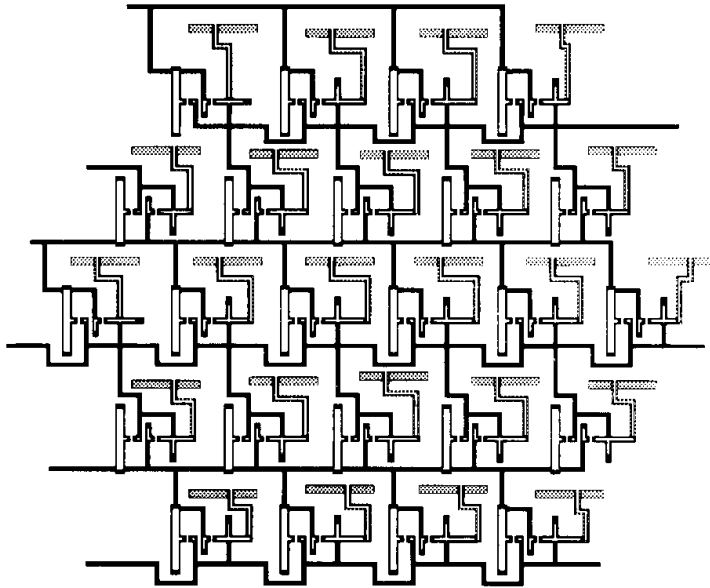


Figure 5. Layout of a slot antenna receiving low noise lens amplifier. The amplifiers in the array are two-stage PHEMT CPW circuits [13].

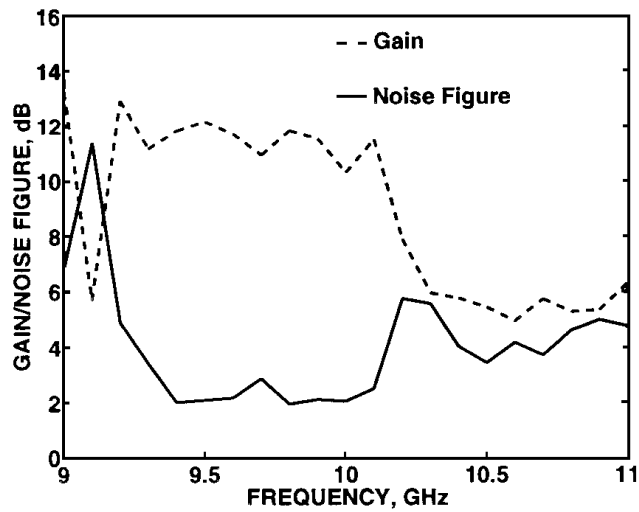


Figure 6. Measured gain and noise figure of the LNA array.

To demonstrate a receiving amplifier, an X-band low-noise PHEMT lens amplifier array using antiresonant slot antennas and two-stage low-noise CPW amplifiers has recently been reported [13]. The amplifier is shown in Fig. 5 and demonstrates 13 *dB* absolute power gain, a minimum 1.7 *dB* noise figure, and 11% 3 - *dB* bandwidth with an average noise figure below 2.3 *dB* in this bandwidth, shown in Fig. 6. The high gain and low noise figure demonstrated by this amplifier are important for maintaining a high SNR, and thus a low bit error rate. The demonstrated 1.1 - *GHz* bandwidth at 10 *GHz* demonstrates the applicability of quasi-optical amplifiers to broadband data communications.

### 3. Discussion

The measured properties of basic components which make up a quasi-optical T/R module were discussed above. A block diagram of a possible quasi-optical transceiver is shown in Fig. 7. It consists of a grid oscillator, such as the one shown in Fig. 1, which acts as a solid-state power-combining source that generates the carrier frequency for the transmitter and also serves as the local oscillator and self-oscillating mixer for the receiver. A planar array of T/R active antennas, such as the ones from Figures 3, 4, or 5, performs the power amplification for the transmit and the low-noise amplification for the receive. Both the input and output waves are focused. Locating the source/mixer at the focal point of the amplifier reduces diffraction loss and thus increases system efficiency. The close proximity of the oscillator and amplifier also allows compact transceiver design. Reliability is improved since the degradation is graceful. This approach is modular, since individual grids or arrays serving different functions can be cascaded into systems.

Modulation can be achieved either through the gate bias of the oscillator or amplifier, or by cascading an external modulator with the amplifier. In [4], a quasi-optical VCO consisting of an array of transistor oscillators stacked with an array of varactor diodes demonstrated good frequency modulation characteristics in a 10% modulation bandwidth with low associated parasitic AM. However, since most modern communications systems are digital, it is important to have digital modulators. A quasi-optical digital phase modulator can be designed based on 3 antenna arrays connected with transistor SPDT switches, allowing 2 bits of phase shift in a single array. The 4 bits required for QPSK can be obtained with two cascaded arrays. We have demonstrated a unit cell of the BPSK modulator with phase shifts of 0° and 150° with no associated transmission loss, as the switches have some gain to overcome the losses.

In order for the quasi-optical amplifier to function as a T/R module, bidirectional amplifier elements need to be used, with transistors placed in



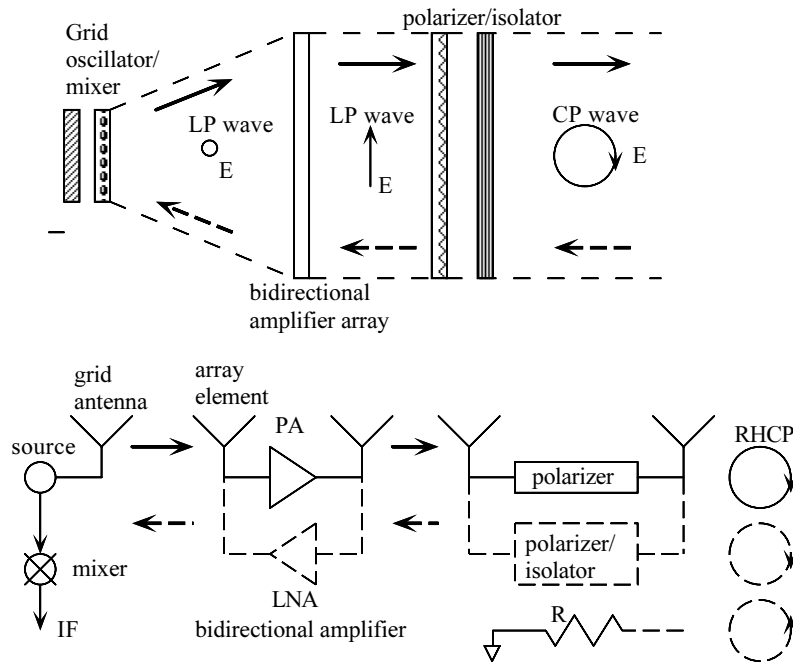


Figure 7. Block diagram of a quasi-optical transceiver. The transmitted signal is shown in solid-line arrows, and the receiving signal path in dashed-line.

opposite directions to amplify the outgoing and incoming waves independently. The transmit amplifier is impedance-matched for maximum power, while the receive amplifier is matched for low noise. (An alternative to using two amplifiers in each element is the grid approach [9], but in this case the amplifier needs to be simultaneously designed for high power/gain and low noise).

The frequency-dependence of the antenna loads is included in the design. The choice of the antenna is an important consideration. Amplifier arrays using folded slots have demonstrated 8% bandwidth [29], while those using a combination of loaded folded slots on the input and anti-resonant slots at the output have demonstrated 11% bandwidth [13]. The second-resonance slot itself has a convenient input impedance of 25 to 100  $\Omega$  and a 20% bandwidth (VSWR=2).

An important issue in local oscillator applications is the phase noise. The overall noise of a grid oscillator should be less than the noise contribution of an individual device, since the grid is self-injection-locked. In addition, since the phase noise of the devices are uncorrelated, the individual noise

contribution of each device in the array should average out. Experimental verification for the single-sideband noise reduction in a 100-element grid was presented in [5].

In the two-level power combining approach shown in Fig. 7, advantages of both oscillator and amplifier combiners are used: the grid oscillator source has improved noise characteristics, while the amplifier array provides large dynamic range. For reception, the noise floor of the entire array is equal to the noise floor of each of the amplifier elements, provided the amplifier noises are uncorrelated. On the other hand, the input power of the array can be  $N$  times larger than that of a single element, as the power gets distributed. This means that for a  $10 \times 10$  array, the dynamic range is increased by 20 dB. In addition, focusing on the receiver end with an LNA array allows for beam-forming in reception by placing mixers at different points along the focal surface. For example, with one mixer positioned at boresight, and two others placed at  $\pm 45^\circ$ , one could receive sum and difference patterns. The reciprocal beam-forming in transmission was already demonstrated with the array from Fig. 3. This allows adaptive processing at the receiver analog front end, increasing the dynamic range of the system.

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