GRID OSCILLATORS WITH PHOTONIC-CRYSTAL REFLECTORS

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Abstract— **The frequency-, polarization-, and reflectivity-dependent properties of photonic crystals are exploited to improve the performance of a grid oscillator. The metal reflector of a C-band grid is replaced with a photonic-crystal reflector, resulting in a higher cross-polarization ratio, higher radiated power, lower harmonic content, and improved start-up conditions.**

I. Introduction

A GRID OSCILLATOR consists of an array of solid-state devices loading a metal grating that is etched onto a dielectric substrate [1]. When properly designed, the grid radiates a linearly polarized wave whose power is the combined output of each device. Such quasi-optical power-combining schemes overcome the limited power-handling capacity of semiconductor devices [2].

The grid is an embedding circuit for the active device that should satisfy the oscillator start-up, steady-state, and maximum-power conditions at the design frequency. To satisfy all of these constraints simultaneously, the grid designer must iterate between the unit-cell geometry, substrate permittivity and thickness, and mirror spacing. In practice, this is a complicated task, since each parameter in some way affects the oscillation frequency, output power, harmonic content, and sidelobe level. Increasing the electrical thickness, for example, can lead to higher power, but can also result in multimoding and can complicate heat removal [3]. Conversely, an electrically thin substrate can eliminate high sidelobes [4], but does not necessarily yield maximum power.

To simplify the design process, this paper proposes expanding the parameter-space by incorporating a reflector that is frequency-, polarization-, and reflectivity-dependent. Fig. 1 illustrates the idea, in which the metal reflector of a conventional grid oscillator is replaced with a photonic crystal (PC).

A photonic crystal [5] is a periodic dielectric structure whose permittivity is spatially modulated, yielding frequency bands in which the incident wave interferes constructively in reflection (giving rise to a stop band) and frequency bands in which the incident wave interferes constructively in transmission (giving rise to a pass band). Since the PC in Fig. 1(b) replaces the metal reflector in Fig. 1(a), the PC should be designed to have a stop band at the desired oscillation frequency.

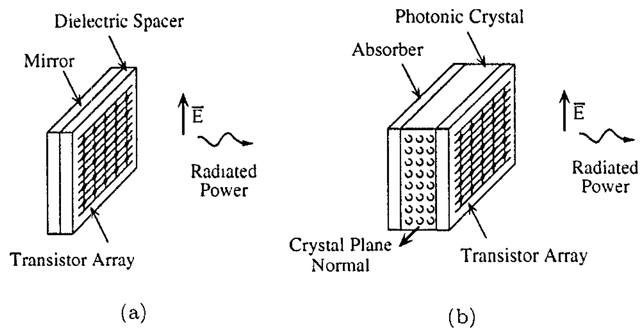

Fig. 1. A grid oscillator using a (a) metal reflector and (b) a photonic-crystal reflector.

Certain features of the PC make it an attractive substitute for the metal reflector in a grid oscillator:

- Since the PC is frequency-dependent, only the desired mode in an otherwise multimoded grid builds up. This is important, for example, in pulsed operation, in which the oscillator should always turn on at the design frequency.
- The PC can be designed to be polarization-dependent (reflecting only the vertical polarization back to the transistor array in Fig. 1), thus improving the cross-polarization ratio.
- The reflectivity of the PC can be set by varying the number of periods in the crystal, allowing the oscillator to operate at the optimum feedback level for maximum power [3]. Alternatively, the reflectivity can be set by allowing the oscillator to operate along the edge of the stop band; this is discussed in Sec. II C.

In Fig. 1(b), an absorbing sheet on the back of the PC terminates undesired (*e.g.*, cross-polarized) back-radiation.

II. Experimental Results

A 5×5 grid oscillator was designed using a full-wave technique based on an infinite-grid approximation [6]. The period of the grid is 8 mm with 1-mm-wide bias lines and radiating leads, and is printed on a 2.54-mm-thick *Duroid* substrate with $\epsilon_r = 10.5$. The active devices are HP-Avantek ATF-35576 pHEMTs.

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A. Grid Oscillator with a Metal Reflector

With a metal reflector placed directly behind the substrate, the grid oscillates at 4.6 GHz with an equivalent isotropic radiated power (EIRP) of 0.07 W, a cross-polarization ratio of 11 dB and a second-harmonic level of -9 dBc. To improve the performance, a 12.7-mm-thick layer of *Stycast HiK* (ϵ_r=10) was inserted between the substrate and mirror. Increasing the substrate thickness had the effect shown in Fig. 2(a), in which the oscillator initially turns on with competing oscillation modes at 4.1 and 6.2 GHz, an effect which is also predicted by linear analysis [3]. The oscillator locks to the 6-GHz mode only after the gate bias is re-adjusted, yielding a higher EIRP of 0.20 W, a larger cross-polarization ratio of 18 dB, and a lower second-harmonic level of -20 dBc (Fig. 2(b)). Locking to the 4-GHz mode could only be achieved through the use of an external variable-reflectance mirror [7].

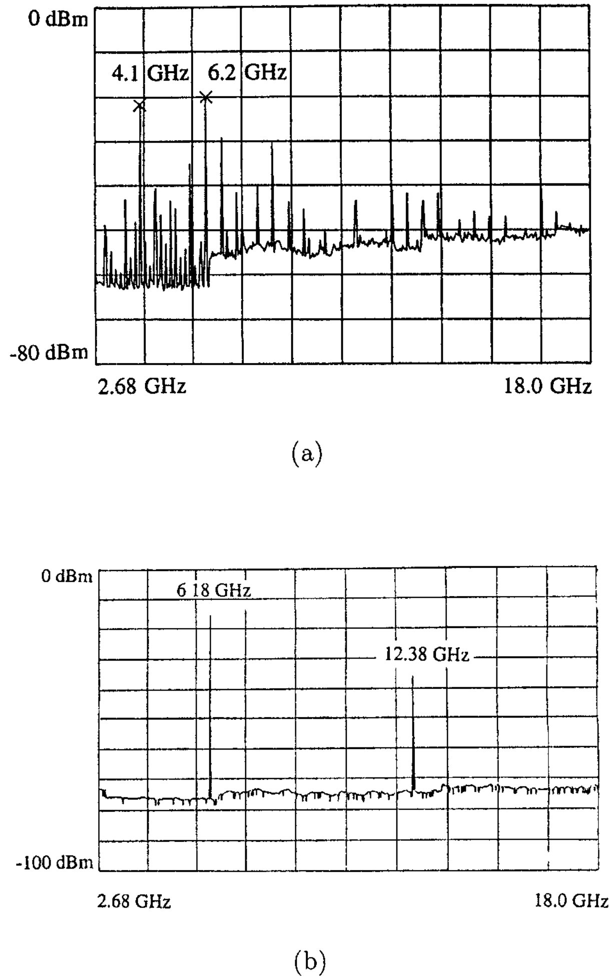

Fig. 2. Measured spectrum of the C-band grid oscillator with a metal reflector showing (a) competing oscillation modes when initially turned on, and (b) the locked oscillator after the dc bias is adjusted.

B. Photonic Crystal Measurements

To determine whether the grid could oscillate at another frequency, a photonic-crystal reflector was designed to replace the metal reflector. The PC was designed for a 4.7–5.8-GHz stop band using an atlas of two-dimensional PCs [8]. The PC topology consists of a square-lattice of air columns (lattice constant = 1.56 cm, radius = 0.59 cm) embedded in *Stycast HiK* (ϵ_r = 10). The PC was specifically designed to have a transverse-electric (TE) stop band [8] to reflect only the co-polar component of the oscillator, whose vertically polarized electric field is transverse to the crystal plane normal of Fig. 1(b). The cross-polar component, whose electric field is parallel to the crystal plane normal, would not be affected by the TE stop band.

The transmission characteristic of the PC was measured using a network analyzer and a pair of wideband horn antennas. Fig. 3 indicates a 25-dB transmission null at the design frequency. This null was nonexistent when both horns were rotated 90°, demonstrating that the stop band was indeed polarization-dependent.

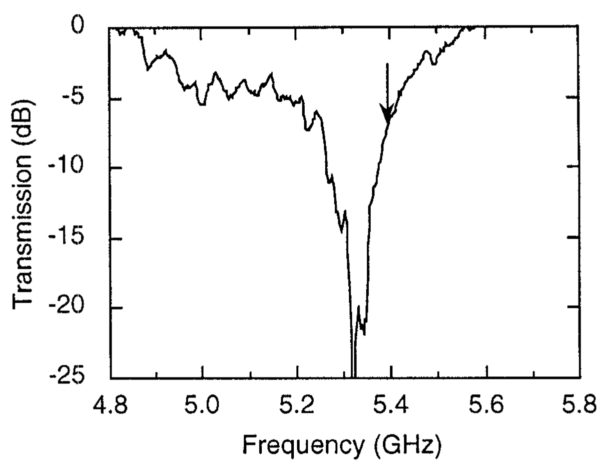

Fig. 3. Measured transmission characteristic of the C-band photonic crystal. The arrow indicates the oscillation frequency of the grid at 5.4 GHz.

C. Grid Oscillator with a PC Reflector

When the metal reflector was replaced with the PC, the unlocked spectrum of Fig. 2(a) was no longer observed. In fact, Fig. 4 shows that the oscillator immediately locks to 5.4 GHz (a frequency which is within the stop band of the crystal) upon applying the dc bias.

The fact that this single-mode oscillation occurs within the stopband of the PC has promising implications in the design process. Designing a grid is often an iterative process. To a large extent, the unit-cell size determines the oscillation frequency. Maximizing

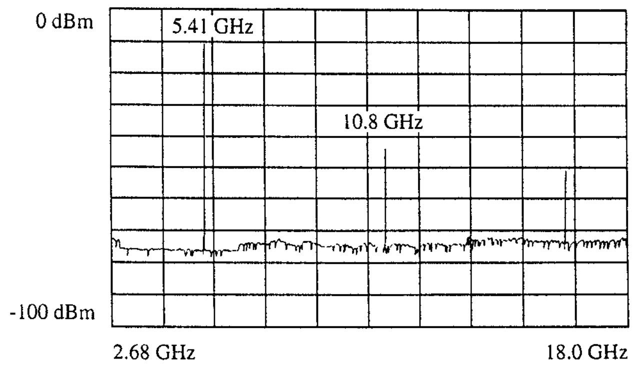

Fig. 4. Measured spectrum of the C-band grid oscillator with a photonic-crystal reflector.

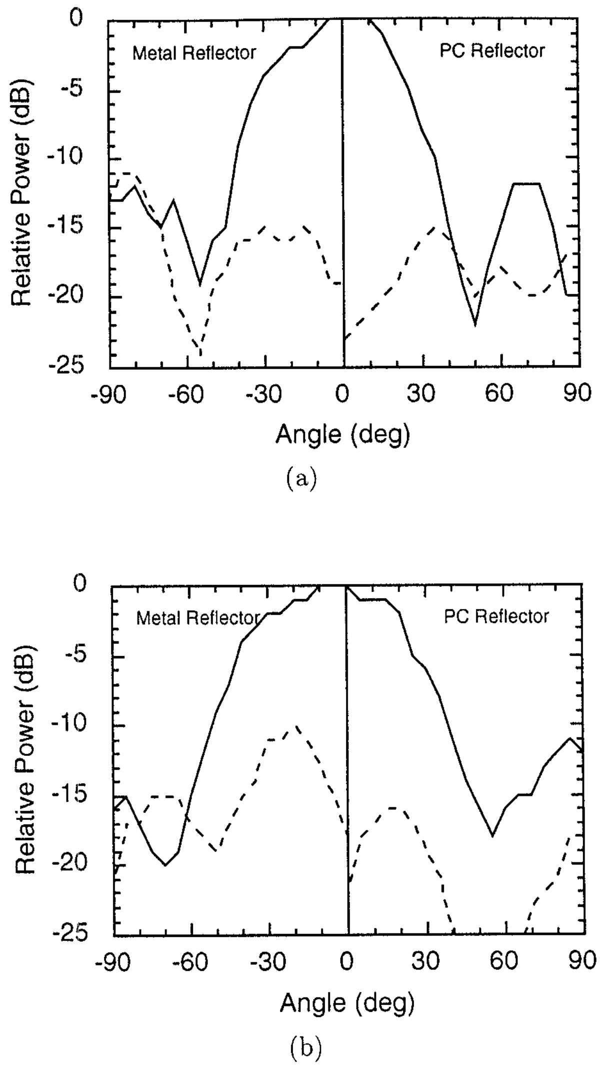

Fig. 5. Measured patterns of the C-band grid oscillator with a photonic-crystal reflector: (a) H-plane; (b) E-plane. The solid line represents the co-polarization, and the dashed line represents the cross-polarization.

the power may dictate varying the substrate characteristics, but this also affects the oscillation frequency, requiring a re-adjustment of the unit-cell size. Several such iterations may be necessary to complete the design. Employing a PC-reflector offers greater flexibility by widening the design parameter space. For example, if the PC stop band is designed to set the oscillation frequency, the unit-cell geometry and substrate characteristics can be left to address other issues, such as suppressing substrate modes [4], without affecting the frequency.

Fig. 5 compares the radiation patterns of the grid oscillator with a metal vs. PC reflector. The main-beam shapes and sidelobe levels are similar in both cases.

Table I summarizes the results comparing the grid oscillator with a metal reflector to that with a PC reflector. With the PC, the cross-polarization ratio at boresight increases by 4 dB, an improvement that we attribute to the polarization dependence of the crystal.

The EIRP for the PC case is nearly three times higher than that of the metal-reflector case. The higher EIRP is not a result of the difference in the directive gain, since the beamwidths in both cases are within 95% of each other. Nor is the higher EIRP a result of dc bias, since the drain voltage for both cases was fixed at 3 V and the drain current for the PC case was only 1.7 times as high.

The reason for the power increase can be explained from the theory in [3]. For the thickness of *Stycast* used in this experiment, circular-function analysis reveals that placing a metal reflector on the back of the *Stycast* yields a feedback level that is too high, resulting in a power level that is less than optimal. Replacing the metal reflector with a PC introduces a mechanism for reducing this feedback. Fig. 3 illustrates the idea. If the oscillation frequency lies in the center of the stop band, where the transmission is a minimum (and reflection is a maximum), then the power reflected back to the grid from the crystal may be too high, resulting in excessive gain compression of the transistors. However, if the oscillation frequency lies on the band-edge, as it does in Fig. 3, the feedback level is reduced, the devices are less compressed, and the output power increases. As

TABLE I

COMPARISON OF METAL VS. PC REFLECTOR

Reflector Type	Osc. Freq. (GHz)	EIRP (W)	Cross-pol Ratio (dB)	2nd Harmonic (dBc)
Metal	6.2	.20	18	-20
PC	5.4	.55	22	-32

a result of the lower compression, the second-harmonic levels are also reduced, as Table I shows.

III. Conclusions

This paper demonstrated how replacing the metal reflector in a grid oscillator with a photonic crystal resulted in a higher cross-polarization ratio, higher radiated power, reduced harmonic content, and improved start-up conditions for a C-band grid oscillator. It was also pointed out how the design process is made more flexible by introducing a frequency-dependent, polarization-dependent, and reflectivity-dependent reflector.

For a grid oscillator with a PC-reflector replacing the metal reflector, an important issue requiring further consideration is heat removal. Heat-sinking could be achieved by fabricating the PC from a thermally conductive substrate such as aluminum nitride and forcing air or liquid through the PC's air columns.

References

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