PHOTONIC-BANDGAP STRUCTURES IN QUASI-OPTICAL POWER-COMBINING ARRAYS

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Abstract

This paper reviews the integration of photonic-bandgap (PBG) structures with active quasi-optical arrays for millimeter-wave transmitter and receiver front ends. The PBG structures allow feedback optimization and multidirectional operation for grid oscillators, and reduced injection locking for self-oscillating grid mixers.

1. Introduction

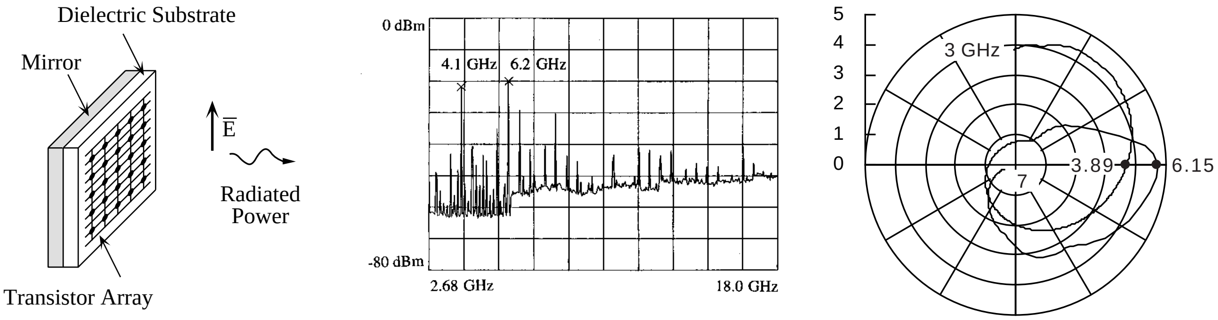
In the quasi-optical power-combining approach [1], the outputs of hundreds or possibly thousands of semiconductor devices are combined in free space, yielding an elegant technique for realizing integrated circuit-antenna arrays for emerging millimeter-wave communications. The dense spacing between devices, typically a small fraction of a wavelength, compensates for their limited output power that decreases with a $1/f$ to $1/f^2$ frequency dependence: the higher the frequency, the closer the spacing, and therefore the greater number of devices that can be packed per unit area. The large number of devices also implies that quasi-optical arrays are intolerant to single-point failures.

One example of a quasi-optical power combiner is the grid oscillator [2] shown schematically in Fig. 1(a), where a metal grid is loaded with transistors. When dc bias is applied to the horizontal leads, an oscillation is triggered by transients or noise, and each device oscillates at a different frequency. RF currents on the vertical leads result in radiation away from the grid. Feedback from the mirror provides the injection locking between devices. Although the intent is to create a single-frequency source, a grid will occasionally support multiple oscillation modes. For example, a grid demonstrated in [3] has the steady-state spectrum shown in Fig. 1(b), in which the oscillator turns on with competing oscillation modes at 4.1 and 6.2 GHz, an effect that is also predicted from a quasi-linear loop analysis [Fig. 1(c)]. The oscillator locks to the 6-GHz mode only after the dc bias is re-adjusted.

2. PBG Structures for Oscillator Optimization

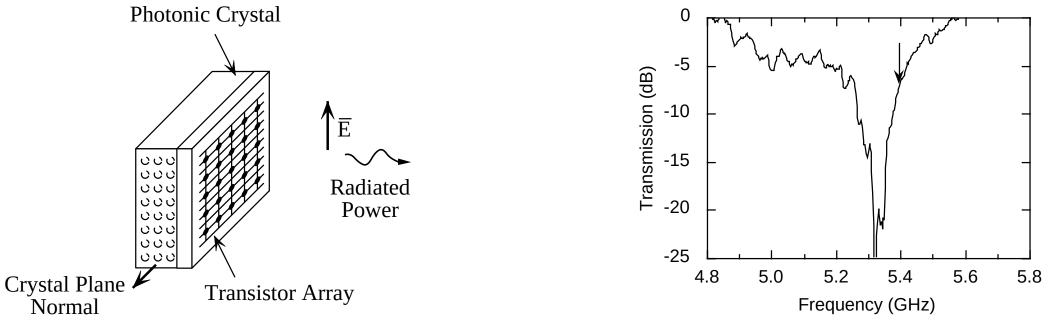
Fig. 2(a) illustrates a more flexible approach that replaces the metal mirror, which has a fixed reflectivity for all frequencies and polarizations, with a photonic-crystal [4] (PC) mirror whose reflectivity is both frequency- and polarization-dependent. The frequency dependence of the PC mirror allows only the desired mode in an otherwise multimoded grid to build up. The polarization dependence allows the cross-polarization ratio to be improved.

A PC was designed for a 4.7–5.8-GHz stop band using an atlas of two-dimensional PCs [5]. The PC topology consists of a square lattice of air columns (lattice constant = 1.56 cm, radius = 0.59 cm) in *Eccostock HiK* ($\epsilon_r = 10$). The PC was specifically designed to have a transverse-electric (TE) stop band [5] to reflect only the co-polar component of the oscillator, whose vertically polarized electric field is transverse to the crystal-plane normal of Fig. 2(a). The transmission characteristic



(a) (b) (c)

Figure 1: A grid oscillator: (a) configuration, (b) measured spectrum, and (c) loop analysis.



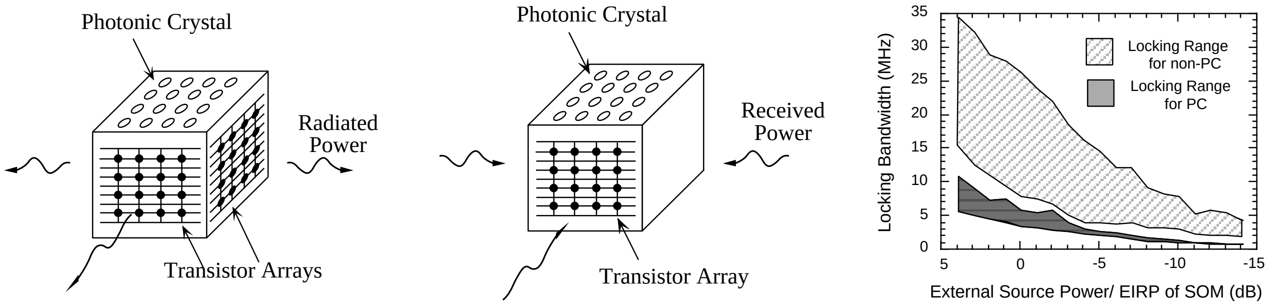
(a) (b)

Figure 2: (a) Grid oscillator with a PC mirror; (b) measured transmission characteristic of the PC. The arrow indicates the oscillation frequency of the grid at 5.4 GHz.

of the PC was measured using a network analyzer and a pair of wideband horn antennas. Fig. 2(b) indicates a 25-dB transmission null at the design frequency. This null is nonexistent when both horns are rotated 90°, demonstrating that the stop band is indeed polarization-dependent.

When the metal reflector is replaced with the PC, the unlocked spectrum of Fig. 1(b) is no longer observed. In fact, upon applying the dc bias, the oscillator immediately locks to 5.4 GHz. The fact that this frequency lies within the stop band of the PC implies that the mirror itself can be used as a design parameter for setting the oscillation frequency, leaving the unit-cell geometry and substrate characteristics to address other issues, such as the suppression of substrate modes.

Compared to the case of a metal reflector, the grid oscillator with a PC reflector demonstrates nearly three times higher equivalent isotropic radiated power and 4 dB improvement in cross polarization. The reason for the power increase can be explained from the theory in [6]. For the thickness of *Eccostock* used in this experiment, analysis reveals that placing a metal reflector on the back of the *Eccostock* 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. If the oscillation frequency lies in the center of the stop band, where transmission is minimum and reflection is maximum, then the power reflected back to the grid from the PC may be too high, resulting in excessive gain compression of the transistors. If the oscillation frequency instead lies along the band edge, as in Fig. 2(b), the feedback level is reduced, the devices are less compressed, and the output power increases.



(a) (b) (c)

Figure 3: Three-dimensional (a) source and (b) self-oscillating mixer consisting of transistor arrays mounted on opposite faces of a PC cube; (c) injection-locking bandwidth vs. external source power for the self-oscillating mixer. Shaded regions correspond to a range of dc bias conditions.

3. PBG Structures for Reduced Injection Locking

One of the consequences of operating along the band edge of the PC is backside radiation. If the back-radiation from one grid is used as an injection-locking source for a second grid mounted on the opposite side of the PC, bidirectional radiation is possible [7]. In fact, the concept of using backside radiation as injection-locking sources can be extended to four oscillator arrays on four sides of a PC cube, with each grid mutually injection locking the others [Fig. 3(a)]. While this configuration demonstrates multidirectional radiation, an improved quasi-optical architecture demonstrating better omnidirectionality is reported in [8].

In addition to operating as a source, the PC-mounted grids can also work as a receiver in self-oscillating mixer (SOM) mode. Although the concept of self-oscillating transistor mixers is at least 20 years old [9], it has continued to be of interest in recent years [10]–[12]. In [9], Tajima noted that one of the difficulties in SOMs is in obtaining sufficient oscillation amplitude at a bias condition (typically class B [10], [11]) where nonlinearity is strongest. Therefore, a quasi-optical SOM that combines the power of several devices may offer significant advantages.

A quasi-optical SOM is shown in Fig. 3(b), in which two transistor-loaded grids are mounted on opposite faces of a PC cube [13]. Measurements indicate that this SOM is capable of detecting incoming RF signals in all directions, allowing three-dimensional angle diversity to be achieved. The SOM was capable of producing IF frequencies up to 3.5 GHz, and a minimum isotropic conversion loss of 27 dB was obtained for an IF frequency of 500 MHz. A quasi-optical SOM with isotropic conversion gain has been reported elsewhere [10], [14].

If the external RF source has sufficient power at a frequency sufficiently close to that of the SOM, the free-running oscillation frequency of the SOM can injection lock to the external source, and the IF will cease to exist. The existence of this injection-locking mechanism is a serious disadvantage of all SOMs, as it limits the range of RF signals that can be downconverted. For the SOM presented here, the PC plays a critical role in overcoming this problem. Measurements of the injection-locking bandwidth (ILBW) were performed with the transistor arrays mounted on both PC and non-PC (solid *Eccostock HiK* dielectric) cubes. The ILBW was observed to be dependent on the dc bias of the SOM; lower-current operation of the SOM led to a wider ILBW. Hence, the bias conditions were varied for both cases with different external RF source power levels to obtain the locking regions in Fig. 3(c).

Comparing the performance of the SOM mounted on PC and non-PC cubes, the reduction in ILBW obtained with a PC is clearly evident. In fact, even the maximum ILBW obtained with the PC-mounted grids is less than the minimum ILBW for solid-dielectric-mounted grids. The reason for the reduced ILBW is that the free-running oscillation frequency is restricted to the narrow stopband of the PC, minimizing its injection locking to an external source whose frequency lies outside of this band.

4. Conclusions

This paper reviewed the integration of PBG structures with active quasi-optical arrays. Feedback optimization and multidirectional radiation were demonstrated by operating a grid oscillator along the band edge of a photonic crystal. Reduced injection-locking bandwidth was achieved for self-oscillating grid mixers mounted on the faces of a photonic crystal.

Acknowledgments

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