

Automatic Beam Scanning in Mode-Locked Oscillator Arrays

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1. INTRODUCTION

Mode-locking refers to a situation where a number of equally spaced spectral modes are simultaneously produced and "locked" in phase, thereby producing a periodic train of pulses. Recent experiments have shown that coupled-oscillator arrays can be similarly mode-locked [1-2], and have been found to possess an additional beam-scanning property. Such arrays thus have great potential for engineering compact solid-state millimeter-wave radar systems.

The superposition of a set of $N = 2n + 1$ equally-spaced spectral modes can be written as [3]

$$E(t) = \sum_{i=-n}^n E_i \exp \{j(\omega_i t + \phi_i)\} \quad (1)$$

The mode frequencies and phases are set according to

$$\omega_i = \omega_0 - i\Delta\omega \quad i = -n, \dots, n \quad (2a)$$

$$\phi_i - \phi_{i-1} = \Delta\phi \quad (2b)$$

where $\Delta\omega$ and $\Delta\phi$ are constants. When the amplitudes are the same, $E_i = E_0$, then (1) and (2) can be combined to give

$$E(t) = E_0 \frac{\sin [N(\Delta\omega t + \Delta\phi)/2]}{\sin [(\Delta\omega t + \Delta\phi)/2]} \exp(j\omega_0 t) \quad (3)$$

which has the form of a carrier signal at a frequency ω_0 modulated by a periodic train of pulses, with pulse repetition frequency $\Delta\omega$. The peak power in each pulse is found to be $E_0^2 N^2$, or N^2 times the available power from a single mode. The phase difference $\Delta\phi$ has the effect of shifting the pulse train in time.

2. MODE-LOCKED OSCILLATOR ARRAYS

In a mode-locked oscillator array, each oscillator represents one mode of the system, and the frequencies of these oscillators are adjusted to produce a comb spectrum according to (2a). It might appear that such a system would require

infinitely precise control over the oscillator frequencies. However, the mutual coupling between oscillators helps establish not only the correct frequency distribution, but also the correct phase relationship. This can be explained qualitatively with reference to figure 1, which shows the spectrum of two coupled oscillators which are not synchronized. Beat frequencies are generated because of the device nonlinearities. Armand [4] has shown that there is a *constant phase progression* among these additional spectral components. The crucial observation is that these sidebands can be used to injection-lock other oscillators in a system, thus enforcing the key requirements for mode-locking (2).

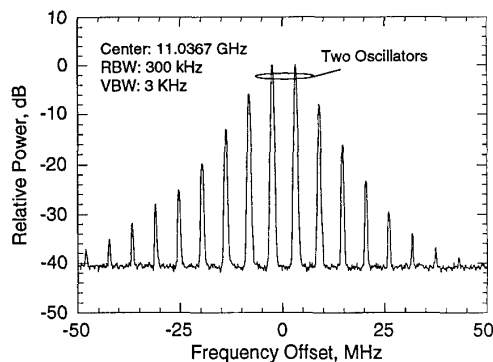


Figure 1 — Frequency spectrum of two coupled oscillators. Mutual pulling effects give rise to a number of additional spectral components, which can be used to injection-lock other oscillators.

3. AUTOMATIC BEAM-SCANNING

The mode-locked arrays concept can be realized using quasi-optical oscillator arrays [5], where each oscillator contains a planar radiating structure, and the energy is combined in free-space. Unlike a mode-locked laser, the different spectral components in a mode-locked antenna array are also spatially separated, and this gives rise to the phenomenon of automatic beam scanning. Using simple array theory, the total electric field above the array is written as

$$E(r, \theta, t) = \sum_{i=-n}^{+n} E_i G(\theta) \exp \{j[\omega_i t + \phi_i + ik_0 \Delta d \sin \theta]\} \quad (4)$$

where k_0 is the free-space propagation constant, $G(\theta)$ is the gain function of each antenna element, Δd is the antenna separation, and θ is the observation angle measured from broadside. Assuming the conditions (2) and equal

amplitudes gives the following expression

$$E(r, \theta, t) = E_0 G(\theta) \frac{\sin [N(\Delta\omega t + \Delta\phi + k_0 \Delta d \sin \theta)/2]}{\sin [(\Delta\omega t + \Delta\phi + k_0 \Delta d \sin \theta)/2]} \exp j\omega_0 t \quad (5)$$

which has the form of a time-dependent array pattern. Equation (5) has been plotted in figure 2 for a five-oscillator patch antenna array, at several time increments during one cycle of the pulse train; a simple patch model has been assumed, and the element spacing is one-half the free-space wavelength. Note from (5) that the amount of scan coverage is determined by the element spacing Δd and the gain function $G(\theta)$. If all the oscillators were located at a single point ($\Delta d = 0$), there would be no beam scanning.

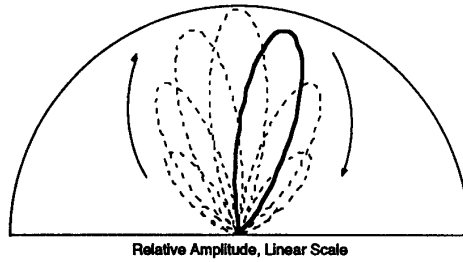


Figure 2 — Polar antenna plot simulating pulse scanning for a five-element mode-locked array, using patch antennas. The elements are spaced one-half wavelength apart. Only the main lobes have been drawn for clarity, at equally spaced time increments over one cycle.

Mode-locked arrays have been demonstrated experimentally [1]. The measured power envelope at three different scan angles is shown in figure 3, for a linear array of Gunn diode/patch antenna oscillators. This measurement was made using the envelope detection feature of a high-speed sampling oscilloscope (Tektronix CSA803). Also shown for comparison is the theoretical expression (5), with good agreement observed between the theory and measurement.

4. CONCLUSIONS

A new and simple technique for producing a monolithic beam-scanning system has been presented. This technique applies the principles of mode-locking to arrays of coupled antenna/oscillator structures. No phase-shifters are required to achieve this beam-scanning. In addition, it can be shown that this beam scanning property applies to both the transmit and receive functions. Using

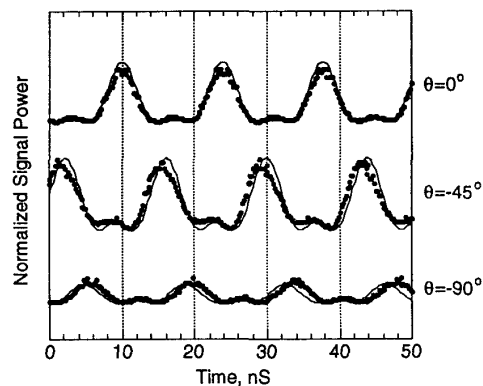


Figure 3 — Pulse waveforms for a three element patch array at three scan angles. The time-shifted pulse at the different scan angles clearly indicates the predicted scanning behavior, and the theory shows excellent agreement to the measurements.

these principles, it may be possible to create very compact and efficient solid-state millimeter-wave radar systems. A more detailed theoretical treatment, and more experimental results will be presented at the conference.

5. REFERENCES

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