2-D array of coupled oscillating elements. Each oscillator with its antenna forms
a single frequency and next, to set a desired phase shift between the adjacent
nearest neighbors and there is no high-frequency global routing to any oscillator.

In traditional phased arrays as the number of rows and columns increases, the
beam steering at any desired direction.

Address issue, this work presents a novel scalable system for THz signal
generation and radiation. Figure 14.6.1 shows the architecture consisting of a
2-D array of coupled oscillating elements. Each oscillator with its antenna forms
a small THz radiator. While independently radiating, each element is also
unidirectionally coupled to its neighboring elements in both horizontal and
vertical directions through variable phase shifters, \( \psi_{\text{row}} \) and \( \psi_{\text{col}} \), respectively.

In this coupled network, the phase and frequency of each element of the array
are related to their neighboring elements through a two-dimensional version of
Adler’s equation shown in Fig. 14.6.1. Based on this equation two scenarios are
conceivable: If all coupling phases \( \psi_{\text{row}} \) and \( \psi_{\text{col}} \) are equally changed, the
locking frequencies of oscillators change while their respective phases, \( \varphi_i \), remain
the same. This dynamic is similar to the delay-coupled oscillators we
introduced in [1]. For example, if all coupling phases increase by the same
amount, the frequency of all oscillators decreases to keep the phase difference
between oscillators constant. On the other hand, as shown in Fig. 14.6.2, by
changing the coupling phase shifts in a differential manner, the relative phase
change of adjacent oscillators changes while the frequency remains constant. A
differential control of the horizontal and vertical phase shifts changes the phase shift of
the columns and rows of the network, respectively. Since these differential phase shifts are independent, by combining them it is possible to simultaneously control the phase difference of adjacent rows and columns of the coupled system. This enables the radiated beam to steer in both polar directions. Hence, by changing the phase shifts together or differentially, we can independently control the frequency and the direction of the radiated beam.

To ensure a symmetric array, the injected energy into each oscillator and the output load should be the same among all oscillators. This is achieved by doubling the magnitude of the coupling blocks (by placing two of them in parallel) on the edges of the array as shown in Fig. 14.6.1. In this way while the oscillators are located in different parts of the lattice, they are all subject to the same frequency and phase shift dynamics.

Each oscillator is a cross-coupled pair that delivers its output power to a
matched radiator designed at the fourth harmonic of the fundamental frequency.
As shown in Fig. 14.6.5, the lines connecting the gates and sources of the core
device and the output load compose a distributed multi-port circuit. At the
fundamental frequency, this network is optimized to maximize the voltage swing
and the outgoing coupled energy. At the fourth harmonic the network is designed to deliver the maximum available harmonic power to the antenna.

The coupling phase shifters inject energy at the fundamental frequency from each given oscillator to two of its four neighbors. The other two adjacent nodes inject energy into that oscillator. In order to effectively absorb the half-wave-length separation between adjacent oscillators, we implement a distributed phase shifter shown in Fig. 14.6.3. The phase shifter consists of an artificial transmission line that is only impedance-matched at the input side, resulting in a resonant antenna connected to a VDI WR-2.2HM harmonic mixer. The 12th harmonic of the LO is mixed with the received signal and downconverted into the IF band. The measured central frequency of the oscillator is 338GHz and the measured phase noise is -93dBc/Hz at 1MHz offset frequency. The low phase noise is a direct result of the topology of the system that couples multiple sources. Adjusting the coupling phase shifters provides 2GHz of frequency tuning. The frequency tuning range can be increased to 7GHz (333GHz to 340GHz) by changing the
temperature by \( \pm 10\% \). To measure the radiation patterns shown in
Fig. 14.6.5, we use the VDI WR2.2-2BD detector and rotate the chip in both angles with respect to the detector. Our measurement confirms that the differential control of the phase shifters keeps the frequency constant while steering the radiated beam across the 2-D angles. The measured beam-steering is 45 degrees along the \( \theta \) axis and 50 degrees along the \( \phi \) axis as shown in
Fig. 14.6.2. By utilizing multiple active stages, one can increase the injected energy from the phase shifters and achieve a wider tuning range or beam steering. To measure the radiated power, we use the Ericson PM4 power
detector. As shown in Fig. 14.6.4, we measure the radiated power both as a function of the control voltage in a fixed direction to the antenna and as a function of direction for a fixed control voltage. The measured peak EIRP of the chip is
\( +17.1\text{dBm} \) at 338GHz. By reducing the antenna gain derived from the measured beam pattern, the peak total radiated power from the chip is 0.8mW. Figure 14.6.6 compares the performance of the circuit with prior art. This lensless source demonstrates the highest radiated power and EIRP as well as the lowest phase noise among the CMOS arrays above 200GHz shown in the Table.

Moreover, the proposed technique provides an effective way to realize a scalable THz phased array with independent frequency control and beam steering.

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References:
[2] R. Han and E. Afshari, “A 260GHz Broadband Source with 1.1mW Continuous-Wave Radiated Power and EIRP of 15.7dBm in 65nm CMOS,” ISSCC Dig.
[3] K. Sengupta and A. Hajimiri, “A 0.28 THz 4x 4 Power-Generation and Beam-
Triple-Push Source in a 65nm CMOS Technology,” European Solid-State Circuits

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Figure 14.1: A 4 x 4 THz phased array based on locally coupled oscillators.

Figure 14.2: The concept of beam steering in a coupled loop, and the measured beam steering in the 4x4 structure.

Figure 14.3: The core oscillator along with inter-connecting phase shifters.

Figure 14.4: Chip measurement setup and the measured output power and frequency.

Figure 14.5: Measured beam pattern and directivity at different steering angles.

Figure 14.6: Performance comparison with prior art.

Table 14.1: Performance comparison of THz phased arrays.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>This Work</th>
<th>[1]</th>
<th>[2]</th>
<th>[3]</th>
<th>[4]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>338</td>
<td>290</td>
<td>260</td>
<td>280</td>
<td>288</td>
</tr>
<tr>
<td>Total Power (dBm)</td>
<td>-0.9</td>
<td>-1.2</td>
<td>0.5</td>
<td>-7.2</td>
<td>-4.1</td>
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<tr>
<td>Peak EIRP (dBm)</td>
<td>17.1</td>
<td>N/A</td>
<td>15.7</td>
<td>9.4</td>
<td>N/A</td>
</tr>
<tr>
<td>Frequency Tuning (%)</td>
<td>2.1</td>
<td>4.5</td>
<td>1.4</td>
<td>3.2</td>
<td>Non-tuning</td>
</tr>
<tr>
<td>Phase Noise (dBc/Hz) (at 0.1Hz offset)</td>
<td>-93</td>
<td>-78</td>
<td>-78.3</td>
<td>N/A</td>
<td>-87</td>
</tr>
<tr>
<td>Beam Steering (degree of each angle)</td>
<td>45/50</td>
<td>N/A</td>
<td>Fixed</td>
<td>80/80</td>
<td>Fixed</td>
</tr>
<tr>
<td>DC Power (W)</td>
<td>1.54</td>
<td>0.33</td>
<td>0.8</td>
<td>0.81</td>
<td>0.28</td>
</tr>
<tr>
<td>Technology</td>
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<td>65nm bulk CMOS</td>
<td>65nm bulk CMOS</td>
<td>40nm SOI CMOS</td>
<td>65nm bulk CMOS</td>
</tr>
<tr>
<td>Area (mm²)</td>
<td>3.9</td>
<td>0.36</td>
<td>2.25</td>
<td>7.2</td>
<td>0.32</td>
</tr>
</tbody>
</table>

1 Power measured by probing.
11 A Hemispheric lens is used for back-side radiation.
111 Substrate-thinning used for front-side radiation.
1111 1.3W for radiators and 24mW for couplings.
Figure 14.6.7: Chip micrograph.