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Photonic-enabled Millimeter-wave Phased-Array Antenna with True Time Delay Beam-steering

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Abstract

We report a photonics-based two-element antenna array operating in the 50 to 120 GHz frequency range wideband emitter module, using a monolithic two-element uni-travelling carrier photodiode array coupled to a pair of high gain planar antennas. The measurements show a record 3-dB bandwidth of 70 GHz, covering three millimeter range waveguide bands (V, E and F). Moreover, we demonstrate that this emitter is a phased-array antenna by performing photonics-enabled beam-steering. By exploiting photonic true time delay technique, beam scanning in 20° range at 70 GHz is proven with only two antenna elements. The scalable and compact module presented allows for realization of compact RF front-end for microwave photonic systems.

1 Introduction

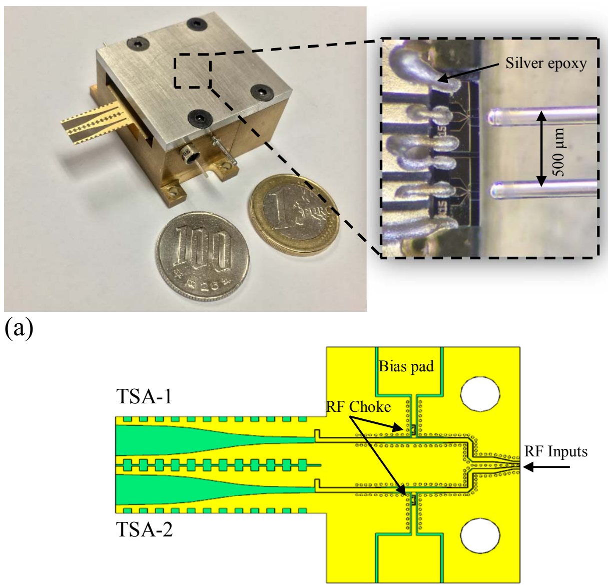
The millimeter wave (mm-Wave) and terahertz (THz) frequency bands provide extremely wide bandwidths to increase the capacity of future wireless communication systems. These frequency bands have received great interest for short-to-medium range multi-Gbps wireless communication links. In future cellular networks' front/backhaul access, i.e. 5G, the RF and baseband signals can be transported over optical fiber cable to the remote antenna sites, making the network architecture fairly simple.

In such application scenarios, beam-steering is a required functionality to mitigate the relatively higher path losses at mm-Wave and THz frequencies by providing direction-oriented coverage in point-to-multipoint systems and compensate for antenna misalignment in point-to-point links. However, there remain challenges for the development of photonic RF front-end devices. The antenna-integrated photonics-based emitters have recently been investigated and provided link performance of more than 100 Gbps [1]. A common approach to increase the radiation gain is to either mount the photomixers on electrically large silicon lenses to increase the received power [2, 3] or coupling them to bulky horn radiators [4, 5]. Such antenna structures can hardly be scaled into phased arrays and produce at low cost. Secondly, the electronic techniques for beam-steering include the phase shifters that provide limited bandwidth and lead to beam-squint effect. Realizing integrated emitter arrays for power scaling and beam-steering applications is hence a necessity. In [6, 7], the authors demonstrated mm-Wave beam-steering using all-discrete off the shelf components.

In this work, we demonstrate an integrated broadband photonics-based phased-array antenna (PAA) emitter in frequency range of 50 GHz – 120 GHz, utilizing high speed uni-travelling carrier photodiodes (UTC-PD) with high gain planar antennas. By employing photonic true time delay (TDD) technique, squint-free beam-steering is demonstrated at 70 GHz carrier frequency.

2 Photonic Phased Antenna Array Emitter

The developed integrated PAA emitter prototype is shown in Fig. 1 (a), packaged in a custom housing. Two corrugated tapered slot antennas (TSA), with grounded coplanar waveguide (GCPW) input, are designed on 127 µm thick substrate in 2x1 array, with overall gain of 15.5 dBi, making it alternative to large horn radiators. Fig. 1 (b) shows the overall structure of antennas that are integrated with two UTC-PDs. The electrical coupling between the antenna and the chips is achieved using an electrically conductive epoxy, as an alternative to the wirebonds. This reduces the inductance of thin wires at mm-Wave frequencies.



(a)

(b)

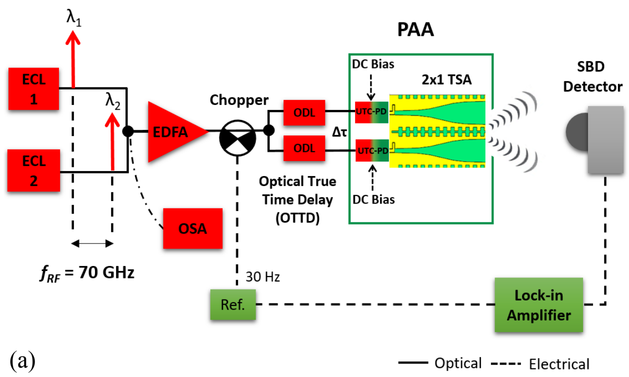
Figure 1: (a) A packaged photonic PAA emitter prototype with antenna and photodiode chips, inset: microscopic view of 2x1 UTC-PD array bonded to the antenna and (b) layout of the designed passive circuit board including 2x1 tapered slot antenna array.

The UTC-PD chips used for this work were fabricated at III-V Lab. They feature an active area of 4 x 15 μm^2, and very high saturation currents, with output RF power up to 0 dBm at 110 GHz. The electrical output is coplanar waveguide with a characteristic impedance of 50 Ω.

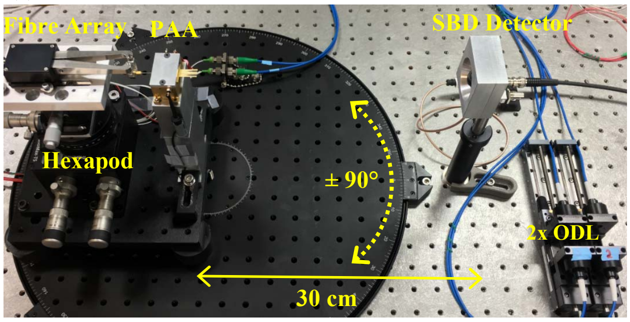
3 Experiment and Results

The PAA emitter is characterized using the experimental setup shown in Fig. 2(a). It includes two tunable external cavity lasers (ECL), providing wavelengths λ_1 and λ_2 with a frequency difference of f_{RF}. The two optical tones are combined and amplified using an erbium doped fiber amplifier (EDFA). An optical chopper then introduces the modulation at 30 Hz for lock-in detection, before splitting into two optical paths. Thereon, tunable optical delay lines (ODL) are used in each of the two paths, leading to optical TTD. The delay $\Delta\tau$ required to steer the radiated beam by an angle θ from the boresight is calculated using (1), where d is the spacing between the antennas and c is the speed of light. The optical signals are fed into the PAA, converted into RF and radiated into free-space. Finally, a Schottky barrier diode (SBD) module detects the mm-Wave signals and the intensity is measured with a lock-in amplifier. To measure the power of radiated waves, a Thomas Keating absolute THz power meter is placed instead of the SBD detector. A picture of setup used to measure radiation patterns in shown in Fig. 2(b).

$$sin\theta = \frac{\Delta\tau}{d}c \quad (1)$$



(a)



(b)

Figure 2: (a) Schematic diagram of the experimental arrangement for photonic-enabled beam-steering and (b) picture showing the laboratory setup for radiation pattern measurement.

First, we measured the frequency response for the integrated emitter module, shown in Fig. 3, by detecting the power in free-space with a calibrated Thomas Keating absolute THz power meter. The graph given here is relative to the peak power detected. The f_{RF} is swept from 53 GHz to 120 GHz with 1 GHz step, while the photocurrent I_{ph} and DC bias voltage V_{bias} are kept constant at 5 mA and -3 V, respectively. We can see that the variations are within the 3-dB over the complete spectral range, providing a 3-dB bandwidth of up to 70 GHz. This corresponds to a fractional bandwidth of 80%, the widest reported ever for an emitter in this range.

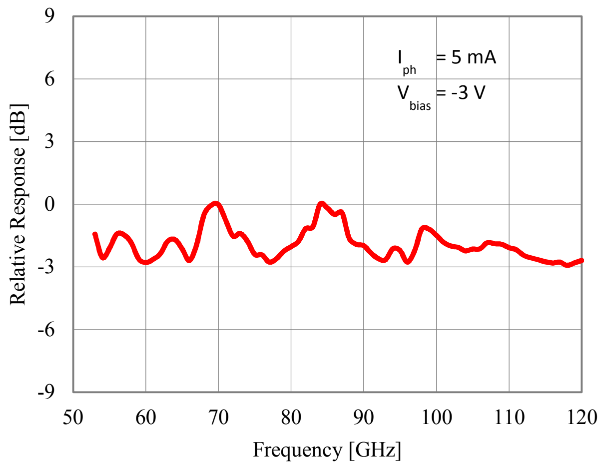


Figure 3: Measured frequency response of the photonic phased-array antenna emitter.

Next, we validate the beam-steering behavior of the PAA module by measuring the radiation patters in far field in the azimuth (E-) plane at f_{RF} of 70 GHz, where the output power is the maximum. Fig. 4 shows the measured beam patterns for the steering angles of -10°, 0° and 10°. Note that very low side lobe level (SLL) is maintained while performing the steering, indicating the possibility of further scanning. The beam-steering also results in a power reduction of -4 and -2 dB at -10° and 10°, respectively, as the SLL increases. The measurement was performed in a laboratory environment, hence the contribution of reflection and scattering in the given data is expected.

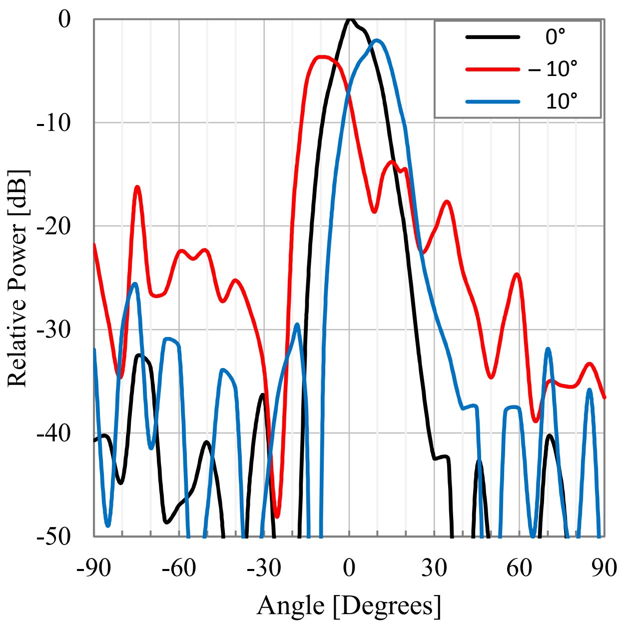


Figure 4: Beam-steering radiation patterns for the angles of 0° (black), -10° (red) and 10° (blue) in azimuth (E-) plane.

4 Acknowledgements

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