A Compact Optically Driven Travelling-Wave Radiating Source

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Abstract: A compact silicon-photonics optically driven mm-wave radiator uses a multi-port driven travelling-wave antenna driven by 8 silicon-germanium photodiodes with -3dB bandwidth of 25GHz to produce -9.7dBm EIRP at 180GHz.
OCIS codes: (190.2620) Harmonic generation and mixing; (250.3140) Integrated Optoelectronic Circuits.

1. Introduction

There is a growing demand for compact and cost-effective generation of mm-wave and sub-mm-wave electromagnetic (EM) radiation with growing applications in communication, imaging, sensing, and ranging. Two candidates are: the all-electrical approach in low cost silicon-based electronics (e.g., [1-3]) and optoelectronic mixing of two signals with close wavelengths. In either case, the coupling of electromagnetic energy from an on-chip generation source to the desired radiative mode is challenging due to substrate modes at those frequencies, making it necessary to use bulky and expensive external components (e.g., silicon lens). Recent development of multi-port driven (MPD) [1] and distributed active radiators (DAR) [2] on the electronic generation of the signal have led to new methods for efficient generation and radiation of mm- and sub-mm-waves from on-chip radiators on a small silicon substrate without an external lens. Similar approaches can be used to produce a compact silicon-based optoelectronic source of sub-mm and THz signals.

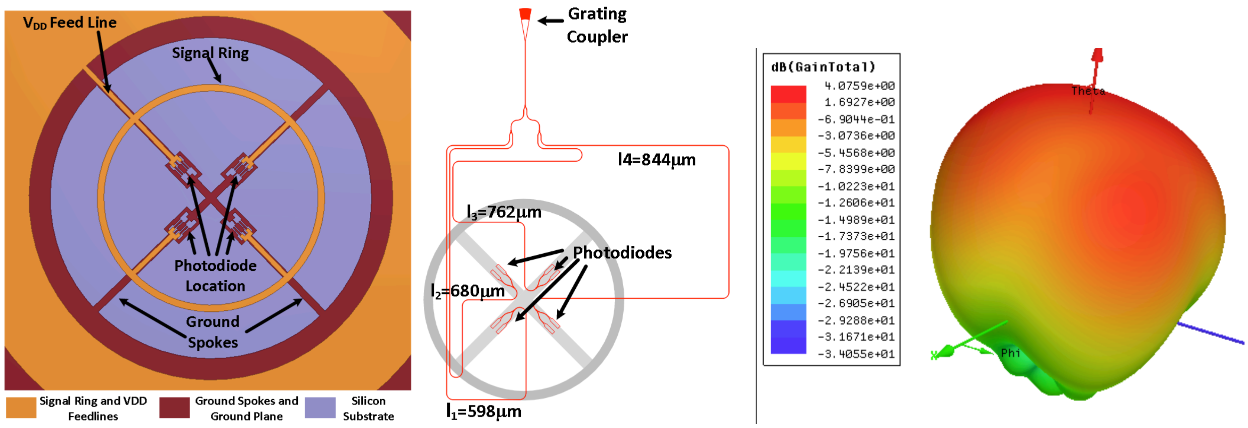
In optoelectronic generation, light with two wavelengths are combined via a photodiode (PD) to produce an output at a mm-wave radio frequency (RF) at their frequency difference in the electrical domain that feeds an antenna. This technique has been used with traditional single-port antennas using external silicon lenses either in a hybrid approach or on non-silicon substrates [4-5].

An optically driven MPD approach can overcome some of the challenges faced by an all-electronic approach, such as the limited frequency tuning range (often a few GHz or lower), higher phase noise (leading to higher bit error rate or reduced image resolution.), power loss in routing of signals and producing necessary phase shifts in an MPD due to the high attenuation of on-chip electrical transmission lines, as well as cross-talk between transmission lines and the radiating antennas, all of which forces the antenna performance away from its optimum. At the same time, it can be used to produce a compact sources without the need for an external lens or antennas, benefiting from the best of both worlds. This is particularly conducive to integrated silicon photonics where the saturated current per diode can be small, making it necessary to divide the optical power and send it to multiple diodes to achieve higher RF power, where an efficiency distributed power combining strategy is a must. The radial multi-port driven (MPD) antenna enables this use of multiple driving PD's and performs impedance matching, power combining and radiation through a single structure [1]. A cohesive co-design of the photonic, electronic, and electromagnetic structures enables greater performance by minimizing loss due to power combining, impedance matching, and power transfer.

2. Radiator Design

The optical MPD radiator consists of a radial MPD antenna, the PD drivers, and an on-chip optical distribution network implemented on a silicon phonics process. The silicon-on-insulator (SOI) process uses a 2μm buried oxide, and a metal stack with 2 layers [6]. The radial MPD antenna is made up of a signal ring that is driven by a pair of PDs at four points against a pair of radially oriented ground 'spokes'. When the currents produced by the PDs are at the correct phase (0°, 90° 180° and 270°), they create a traveling current wave around the signal ring and quadrature phased standing waves along the ground spokes that produce a circularly polarized radiated field as seen in Fig. 1a.

The waveguides are implemented as strip waveguides that are 0.5μm wide and 0.22μm thick. To create the phase shift in the RF signal, the lengths of the optical waveguides are staggered. The phase of the beat signal is dependent on the difference in phases of the optical signals. This means that the physical length of the delay is on the order of the RF wavelength, not the optical wavelengths, and thus mismatch in phase due to process variation or thermally induced index change is decreased by three orders of magnitude ($\Delta f/f$), and each 90° phase delay is 82μm. This delay in the waveguide has a simulated loss of 0.01 dB, much less than the loss of a 90° phase delay produced electrically at these frequencies.



(a) (b) (c)

Figure 1. Layout of optical multi-port driven radiator's antenna (a), optical distribution network (b), and simulated radiation pattern of the antenna gain at 180 GHz..

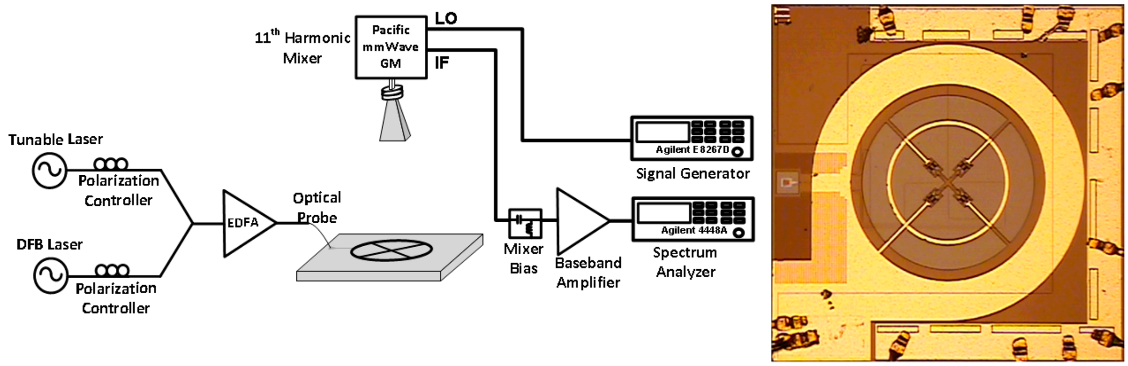
The optical signal is coupled into the chip using a grating coupler with loss of 3-4 dB and is split into four signals using two stages of Y-junction dividers. The silicon waveguides are small enough compared to the wavelength of the RF signal that they have a negligible effect on antenna performance once the signal is converted into the electronic domain, and thus can be routed independently of the antenna design, an advantage of having the input distribution in a different domain from the radiation. The waveguides are routed to the four drive points of the antenna and are split once again with a Y-junction divider just before the diodes, as can be seen in Fig. 1b.

By sizing the ring just larger than one wavelength in circumference, the traveling wave on the ring will have a 180° phase shift as it travels half way around the ring, and will have a 180° change in direction due to the curvature of the ring. This means that at any instant, there will be two maximum currents on the ring at opposite sides that are pointed in the same direction, and these two maxima then rotate around the ring creating the circular polarization. While the currents on the spokes produce standing waves that on their own would be linearly polarized, the phase of the currents on the two orthogonal spokes are in quadrature, so the radiation produced by the currents on the spokes is also circularly polarized, and with correct sizing will be close to in phase with the fields radiated from the ring. The ground spokes connect to an outer ground plane that is pulled back $\lambda/4$ from the ring, which helps to minimize coupling to the substrate modes, and directs most of the current on the ground spokes through the middle of the radiator. The DC power for the diodes is supplied through the signal ring on a $\lambda/4$ transmission line that produces a high impedance looking outward from the ring, thus minimizing the transmission line's effect on the radiation. The simulated radiation pattern of the antenna using Ansoft HFSS FEM solver is shown in Fig. 1c. It shows a single beam that is fairly wide, which is desirable for a single element of an integrated radiator. This means that the element can be placed in a phased array in the future with a large beam steering range.

The 8 photodiodes have a simulated 3dB bandwidth of 25 GHz, limited by the junction capacitance. While the RF power produced by the photodiodes drops above this frequency, the photodiode can still operate at much higher frequencies at lower power levels. The dimensions of the antenna are chosen to maximize output power of the PDs by providing an input impedance near the optimal match.

3. Measurement results

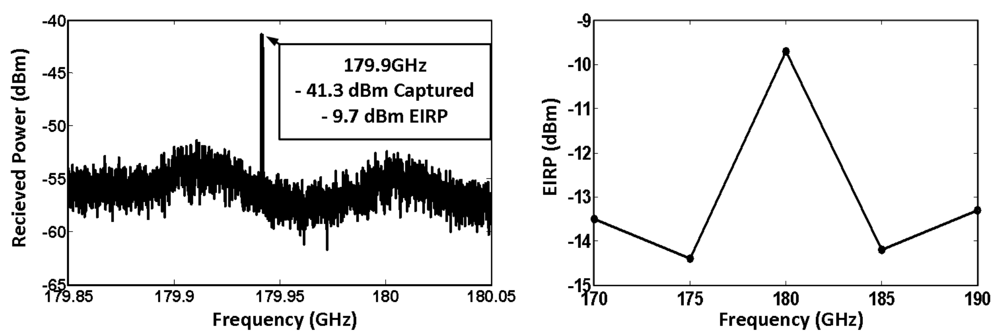
The chips were mounted on a PCB and optically probed, with wire-bonds providing DC biasing. The optical signal was created by combining output from a tunable laser (HP8168E) with the output from a distributed feedback (DFB) laser (NEC NX8562L), both operating in C band. that is then amplified with an EDFA. The optical power going into the optical probe is 750 mW. The radiated signal is received with a WR-5 22dB gain linearly polarized horn antenna located 6cm from the chip that feeds an 11^{th} harmonic mixer. The down-converted signal is amplified and measured with a spectrum analyzer, as shown in Fig. 2. The harmonic mixer is calibrated against a calorimeter based Erikson power meter (PM4). The PDs have a reverse bias of 3V, and a photocurrent of 45mA.



(a) (b)

Figure 2. Measurement setup (a), and die photo of the radiator (b).

The calibrated spectrum at 180 GHz is shown in Fig. 3b, and shows a broadside effective isotropic radiated power (EIRP) of -9.7 dBm. The linearly polarized receive antenna was rotated in the plane parallel to the chip to verify the chip's radiation is circularly polarized. The broadside EIRP is plotted verses frequency in Fig. 3c, and shows EIRP greater than -15 dBm from 170 GHz through 190 GHz.



(a) (b)

Figure 3. Calibrated spectrum of the measured broadside radiation at 180 GHz (a), and measured frequency response of the effective isotropically radiated power (EIRP) in the broadside direction (b).

4. Conclusion

A 180 GHz optically driven MPD radiator implemented in an integrated silicon photonics process was demonstrated to highlight the benefits that optical integration can have on integrated radiators as well as the benefits of a coordinated co-design of photonic, electronic and electromagnetic blocks within the radiator.

5. Acknowledgements

The authors would like to thank OPSIS for chip fabrication.

6. References

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