Controlling On-chip Optical Radiation with All-Dielectric Antennas: Reconfigurable Interconnects and Lab-on-a-chip Devices

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Abstract. Aimed to improve the flexibility of optical network-on-a-chip topologies, unguided optical interconnects using plasmonic nanoantennas or dielectric phased arrays have been proposed. However, the bulky footprints of the latter, and both the low directivity figures and high losses of the former, together with complicated excitation schemes, limit their use for on-chip optical interconnects. Here, we introduce a novel concept of on-chip CMOS-compatible wireless optical system based on the use of smartly engineered broadband easily-fed antennas, which not only overcomes the aforementioned drawbacks but also opens a wide range of applications in several fields. To illustrate its potential, several unprecedented on-chip wireless applications are outlined and experimentally demonstrated. This includes the verification of broadband highly-directive wireless data transmission at speeds as high as 160 Gbit s⁻¹ over mm-scale links, the realization of fully-reconfigurable wireless beam steering device and the validation of an ultra-compact integrated contactless microflow cytometer.

The ceaseless progress in the field of CMOS ultra-large system integration is continuously requiring more energy-efficient and flexible on-chip interconnection networks [1], manufactured at ever tinier scales with pinpoint accuracy. It is well-known that on-chip guided photonic systems can deliver ultra-high-speed low-power solutions for both multi-core interconnections and traffic routing [2].

However, this kind of waveguide-based photonic architectures is not able to provide the necessary flexibility to relax the strict interconnecting design rules of the optical network-on-chip and seamlessly pave the way for much wider range of on-chip applications. Such a limitation stems precisely from the use of waveguides, either plasmonic or dielectric, which confer these networks a fixed static physical topology. Along this line, trying to improve this lack of flexibility, photonic unguided links at the nanoscale have been proposed using plasmonic nanoantennas, as mimicking radiofrequency links [3]. In fact, plasmonic nanoantennas [4,5] have recently emerged as a key piece in nanophotonic circuit engineering due to their capacity to concentrate optical energy at very high frequencies and to prove large spontaneous emission enhancement [6]. Unfortunately, on the one hand, plasmonic nanoantennas exhibit poor directivity and high losses as a result of their strong field confinement and metallic absorption at optical frequencies [7]. Additionally, the excitation of these nanoantennas usually requires complex feeding elements such as quantum dots or nanodipoles [8], which experimentally represents an additional technological challenge. Likewise, we can also find studies based on the use of dielectric antenna arrays [9,10], implemented on vertical grating couplers that attempt to offer a solution for optical data interconnects. From a general perspective, while these configurations allow higher directivity figures, they usually lead to less compact devices, more focused on off-chip data transmission.

The current shortages associated with these implementations reveal that a high-performance new model of wireless optical interconnecting architecture is required to bring efficient solutions in a wide variety of applications. Moreover, such architecture could not only fulfill the current photonic waveguide-based systems demands but also open ground-breaking on-chip photonic applications in several fields. In this work, building on a new concept of smartly-engineered silicon antennas we show the feasibility of the aforesaid high-performance on-chip flexible wireless optical architecture by experimentally demonstrating the first wireless long-reach high-speed on-chip data transmission, a fully-reconfigurable wireless optical system and a contactless photonic microparticle sensor.

The first step for achieving the desired architecture is to develop a kind of antenna exhibiting low loss and low reflections, and whose directivity can be tuned to take a wide range of values able to accommodate different applications, while always keeping a reduced size. For instance, for high-speed data transmission wireless optical links, the directivity must be as high as possible (well beyond the figures reported so far) to increase the optical link reach up to the mm-scale. Recent studies show that nanoantennas based on dielectric nanoparticles exhibit lower losses and a higher directivity than metallic structures [11], although
still too low for the above-mentioned applications. Moreover, these structures present important fabrication challenges. Following this thread, we studied the possibilities of open-end dielectric waveguides as potential radiating elements. Using Huygens’ principle [12], we modelled this kind of structures as aperture antennas, in the same way that microwave metallic waveguides are analyzed. This simple approach links directly the radiation pattern of the waveguide with the propagating mode profile, providing simple design rules that surprisingly allow us to tailor the antenna directivity from values as low as 5 to figures higher than 100 [13]. In addition, the weakly confined modes supported by these structures favor impedance matching, thus minimizing reflections. Finally, the use of dielectric materials guarantees the desired low losses. With this reasoning in mind, we designed several structures based on well-known silicon photonic waveguides [14], namely, strip and slot configurations, ensuring a simple fabrication process using conventional dielectric elements and avoiding other complex feeding structures, usually employed with plasmonic nanoantennas.

We focused primarily on the strip option, since in this case the antenna directivity can be easily tuned by gradually reducing its width through an inverted-taper configuration, which allows a reflectionless transition from a standard 450-nm-wide strip to the radiating end. For the sake of fabrication simplicity and to avoid long taper structures we fixed a minimum taper tip width of 150 nm, which allowed us to attain directivities higher than 50 at near-infrared wavelengths. Moreover, we verified that by using additional elements (directors) [13,15], it is possible to further improve the directivity while keeping a reduced antenna size, see figure 1(a). After an optimization process, we obtained a director configuration consisting of two symmetric silicon strips. The proper combination of a single antenna and the designed directors enhanced the directivity to figures as high as 114. In order to numerically calculate the directivity of the antennas, the fundamental TE mode of a standard 450-nm-width 220-nm-height silicon strip waveguide is excited. This waveguide is directly butt-coupled to the input facet of the antenna, see figure 1(b), being the responsible of feeding the structure, which in turn will radiate under far-field conditions. So as to excite the aforementioned TE mode, standard ports were set up at the input facets to simulate infinitely long waveguides. The rest of the computational domain was terminated with perfectly matched layers (open boundaries) to avoid undesirable reflections.

Figure 1. (a) Directivity of the designed antenna as a function of the number of directors. (b) Artwork of the proposed final silicon antenna design. (c) Schematic top view of the final antenna configuration and directors. (d) SEM image of a wireless point-to-point antenna link with $d = 10$ μm. Calculations were performed by using the CST Microwave Studio Suite.

Note that recent dielectric antennas [11] reach directivity values up to 12, while typical plasmonic nanoantennas exhibit lower values [16]. The final configuration of the antenna including the directors is displayed in figure 1(b). The optimized dimensions of the structures as well as a SEM image of a fabricated link are depicted in figures 1(c) and 1(d), respectively. Note that, as these structures do not rely on resonant phenomena a large bandwidth is also guaranteed. Additionally, these dielectric structures display almost perfect impedance matching in a wide spectral region, as well as a total efficiency close to 90%. Thus, unlike in typical plasmonic works, auxiliary resonant matching elements are not needed, avoiding the bandwidth limitation they introduce. Let us now see how this unprecedented low-loss, broadband, and ultra-directive configuration (not so far achieved with a single optical antenna) can provide novel efficient solutions in a variety of situations.

As a first example, using the previously shown final antenna configuration including two directors, we experimentally achieved, for the first time, a long-reach high-speed wireless data transmission through mm-scale on-chip links consisting of two identical antennas. For this purpose, several samples with different gap distances $d$ (0.1, 0.2, 0.4, and 0.8 mm) were fabricated on a silicon-on-insulator platform. We measured the link power efficiency (see figure 2(a)) as a function of $d$ by injecting light into standard 450-nm-wide strip waveguides (connected to the antennas) using conventional grating couplers and tapers. The experimental antenna gain was also retrieved (see figure 2(b)) and found to be in good agreement with our
theoretical estimation. Digital data transmission over the 0.4-mm link was demonstrated by sending 40 Gbit·s⁻¹ pseudo-random bit sequences at 38 different ITU channels evenly spaced by 0.8 nm, ranging from 1534.25 to 1563.86 nm. We measured bit error rates (BER) below 10⁻⁹ (sufficiently low to rule out forward-error correction schemes often related to an increase in chip complexity) in all cases, verifying the above-mentioned broadband features. This performance shows the feasibility of attaining terabit-per-second data streaming over mm-scale distances by using wavelength multiplexing.

Figure 2. (a) Experimental (blue) and theoretical (red) power efficiency for different distances d. Theoretical results were retrieved by using the Friis transmission equation: \( P_{RX} = P_{TX} \cdot G_{TX} \cdot G_{RX} \cdot (\lambda / (4 \pi d)) \), where \( P_{RX} \) and \( P_{TX} \) are the received and transmitted power of the antennas, respectively. \( G_{TX} \) and \( G_{RX} \) stand for the gain of the transmitting and receiving antennas, \( \lambda \) is the working wavelength and \( d \) is the link distance between the antennas. For comparison purposes, the simulated efficiency corresponding to a bare tapered antenna with no directors is also included for the 100-µm link. (b) Simulated and experimental (retrieved from the measurements) antenna gain. (c) BER measured with an error analyzer and evaluated as a function of the decreasing optical power received by the photodetector for a baseline configuration where the wireless link was replaced with a silicon straight waveguide (left) and for a 100-µm wireless link (right). The 160 Gbit·s⁻¹ BER corresponds to the demodulation of the wavelength corresponding to ITU channel 34 when transmitting channels 33 to 36. The crosstalk produced by surrounding channels (33, 35 and 36) introduces low penalties.

To illustrate this possibility, we additionally transmitted 160 Gbit·s⁻¹ data streams consisting of four decorrelated 40-Gbit·s⁻¹ sequences at wavelengths ranging from 1548.52 nm up to 1550.92 nm (0.8 nm evenly distributed), obtaining the same performance in terms of BER, see figure 2(c). Remarkably, the ultra-directive behavior here shown could permit the implementation of unguided crossings in many different configurations without perturbing the beam propagation or adding any undesired crosstalk (and even leads us to envisage the possibility of achieving efficient inter-core on-chip wireless interconnects), thus providing a much more flexible optical interconnect architecture.

Figure 3 shows a scheme of the set-up employed for the data transmission experiment. Measurements were carried out using a commercial LiNiBO3 modulator fed with a 40 Gbit·s⁻¹ non-return to zero (NRZ) pseudo-random bit sequence (PRBS \( 2^{31} - 1 \)) delivered by a bit pattern generator (SHF BPG 44E). The electrical signal was amplified through a broad bandwidth driver amplifier (DC to 40 GHz) to achieve a voltage swing of ~5 Vpp and combined to a 1.7 V DC offset to ensure the modulator is biased at quadrature. The input Gbit·s⁻¹ modulated signal was then coupled in and out the silicon chip (DUT) via grating couplers, with typical insertion losses below 9 dB at \( \lambda = 1550 \) nm. In addition, silicon tapers were employed to couple
light from the grating to standard 450 nm-wide strip waveguides and vice versa. The signal transmitted through the link was photodetected by a 40 GHz Digital Communication Analyser (Infiniium DCA-J 86100C).

The ever more indispensable requirement for reconfigurable on-chip networks motivated a second application: a dynamically-tunable antenna beam-steering system. To this end, we benefited from a distinctive feature of the proposed architecture, i.e., the excitation scheme based on silicon waveguides. The fact that the refractive index of these structures can be modified dynamically via different effects (e.g., thermo-optic, electro-optic) permits us to tune independently the phase $\alpha$ (and ultimately the amplitude via interferometry) of each antenna’s input signal. Consequently, the use of antenna arrays in combination with any of these effects makes it possible to mold the in-plane radiation diagram in almost any desired way. As an example, we exploited silicon thermo-optic effect\[17\] through the use of metallic nano-heaters, each terminated by two pads and placed atop the feeding waveguides (separated by a 1-$\mu$m SiO$_2$ layer from the substrate), to control the input phase ($\alpha$) of each antenna \[13\]. This is achieved by modifying the temperature of each waveguide through the voltage applied across a corresponding nano-heater. With this simple technique, we experimentally demonstrated a reconfigurable 30-degree beam-steering system over 100-$\mu$m links ($\lambda$ = 1550 nm). Figures 4(a) and 4(b) show SEM images of the transmitting and receiving beam-steering subsystems. The device constitutes a 1-to-3-port switch and, contrary to existing guided solutions \[18\], is completely scalable thanks to its wireless nature, i.e., more inputs/outputs can be added without additional insertion losses \[13\]. In addition, we estimated the device energy consumption and speed, finding a switching power of 8.3 mW for a single heater (three times this value for the complete beam steering device) and a switching time of 5.2 $\mu$s. Note that both values are in line with current state of the art. Moreover, the sharp beams radiated by our ultra-directive antennas yield a very good crosstalk figure (see figure 4(c)). That is, when a beam is steered towards a determined antenna, the power drastically decreases in the non-receiving ones. It is worth to point out that this feature could not be achieved with low-directivity antennas, invalidating the steering device for many applications such as data switching.

Figure 4. (a) SEM image of the waveguides used to feed the 4-antenna emitting array. (b) SEM image of the receiving subsystem consisting of seven antennas placed at different angles. The antennas at 75°, 90° and 105° are taken as the device output ports. The values of $\alpha$ that allow us to steer the beam to each of these ports were estimated to be $-158^\circ$, $0^\circ$ and $158^\circ$, respectively. (c) Total array gain associated with each receiving antenna (d=100 $\mu$m, $\lambda$=1550 nm) for the three values of $\alpha$. Circles indicate measured values at each antenna position. The crosstalk at the output ports is highlighted, with values always better than 8 dB.

As a final example, inspired by the technique employed in flow cytometry \[19\], we designed and fabricated an on-chip hydrodynamic parametric analysis system in which different kinds of microparticles can flow through a microfluidic channel and be simultaneously illuminated by a narrow beam. The main goal was to classify the flowing particles according to their unique time-dependent scattered-field signatures. To this end, we incorporated an optical subsystem to the chip consisting of a highly-directive emitting antenna (inverted taper + 2 directors) and two identical receiving antennas connected to standard strip waveguides, see figure 5(a). One of the receiving antennas collects the power at 90° and is used for alignment/calibration purposes. The second receiving antenna measures the scattered field at 60°, which enables us to classify the particles. On the other hand, a microfluidic channel was built to allow the particles to flow in between the antennas. To test the device, we used polystyrene microspheres (a standard
benchmark for calibrating flow cytometers) with two different diameters (1 and 2 µm) in an aqueous solution with a concentration of 1:100 (2% solids). Capillary forces ensure that the solution fills the channel and the microspheres flow between the antennas when casting a solution drop into the fluidic system. To learn the characteristic scattered-field signature of each kind of microsphere, we prepared two different solutions including either 1-µm spheres or 2-µm spheres alone. Both signatures appear in the form of a dip, of approximately 2 dB in the case of the large microspheres and of 0.25 dB in the case of the small ones, see figures 5(b) and 5(c). The signatures are exclusive, as no 2 (0.25) dB dips were observed when flowing the 1-µm (2-µm) spheres. Finally, an equally-mixed solution containing both kinds of particles was flowed, see figure 5(d). In this case, we were able not only to detect when a particle goes through the optical link (due to the presence of a dip), but also to easily classify such a particle, i.e., identify its size, depending on the magnitude of the measured dip. It is worth mentioning that, since the optical system is not in physical contact with the target, it can be reused an unlimited number of times. Outstandingly, the directive nature of the illuminating antenna implies that very small particles can be resolved, providing a promising solution for sub-micron particle detection. The proposed device constitutes a low-cost chip-integrated type of flow cytometer [20], much more compact than current versions, since no bulky elements such as optical fibers or lenses are required, eliminating potential losses and failure of discrete component interfaces and simplifying the packaging and the automation of the manufacturing process. Finally, the high density of detectors allowed by the small size of the antennas permits a finer scattered-field sampling angular resolution, resulting in a more accurate classification system if necessary.

![Figure 5](image.png)

**Figure 5.** (a) Optical microscope image of the fabricated device. (b–d) Power time-dependent efficiency measured at 60° for 1-µm (b), 2-µm (c), and a mixed solution of polystyrene microspheres (d).

In conclusion, we have experimentally demonstrated a new concept of flexible and reconfigurable wireless optical system built upon a disruptive kind of high-performance silicon optical antennas. This approach provides a CMOS-compatible on-chip platform supporting a wide range of multi-purpose ultra-compact applications hardly manageable via traditional waveguide-based architectures or plasmonic-based implementations, hence opening a new era for the future nanophotonic circuitries and technologies. These applications include flexible wireless high-speed data transmission links and dynamically-reconfigurable optical network-on-chip topologies, with functionalities ranging from antenna beam steering or beam focusing to 2D-selective optical detection or 2D space mapping, as well as integrated contactless sensing systems for realizing lab-on-chip devices.
Fabrication of the samples

The antenna links were fabricated on standard SOI samples from SOITEC wafers with a top silicon layer thickness of 220 nm (resistivity \(\rho \sim 1-10^{12} \text{cm}^{-1}\), with a lightly p-type background doping of \(~10^{15} \text{cm}^{-3}\)) and a buried oxide layer thickness of 2 \(\mu\)m. The fabrication is based on an electron-beam direct-writing process performed on a coated 100 nm hydrogen silsesquioxane (HSQ) resist film. The mentioned electron-beam exposure, performed with a Raith150 tool, was optimised in order to reach the required dimensions employing an acceleration voltage of 30 KeV and an aperture size of 30\(\mu\)m. After developing the HSQ resist using tetramethylammonium hydroxide, the resist patterns were transferred into the SOI samples employing an optimised Inductively Coupled Plasma-Reactive Ion Etching process with fluoride gases.

Finally, a two-micron-thickness silicon dioxide uppercladding was deposited on the SOI sample by using a Plasma Enhanced Chemical Vapour Deposition system from Applied Materials. For the fabrication of the fluidic channel, a Cr layer of 35 \(\mu\)m was first deposited on the SOI sample by using electron beam metal evaporation. A direct writing electron beam exposure of the channel was then performed on a layer of 100 \(\mu\)m of PMMA 950K positive resist. After resist developing, Cr was removed from the channel area using a wet Cr etchant process based on 4HClO4 + 6C(NH4)2(NO3)6 + H2O. Afterwards, an ICP-RIE process was carried out to open the channel through the SiO2. Finally, the sample was cleaned in order to remove the organic residues by a mixture of H2SO4 and H2O2 (3:1) during 20 minutes and then washed by deionized water (DIW). This cleaning procedure was also used to regenerate the device after sensing experiments. To prepare the employed PDMS thin substrates (Sylgard 184 Silicone Elastomer Dow Corning), the PDMS mixture (10:1) was spin-coated on glass cover slides and cured at 60 °C during 1 hour to obtain a thin (150 \(\mu\)m) PDMS layer on the glass slide. After the curing process, the PDMS was peeled off from the glass slide and washed in absolute ethanol to clean the surface. Finally the PDMS substrate was positioned and aligned on top of the fluidic channel.

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