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Optical vortices for photonic integration

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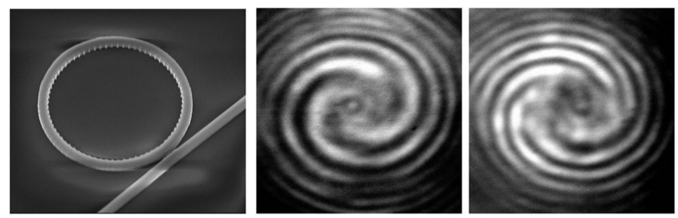
Integrated arrays of novel micron-sized emitters produce multiple photons with precisely controllable orbital angular momentum and potential applications in signal processing.

Optical vortices are light beams made of photons that carry orbital angular momentum (OAM),[1] the same kind of inertia that keeps the Earth orbiting the Sun. The OAM of photons can have important applications in information technology, where the OAM values can carry information in addition to other parameters of light,[2] such as intensity, frequency, and phase. OAM can also have unique applications in manipulation of microscopic particles because of its ability to spin and rotate these particles.[3] To generate OAM beams, scientists have traditionally relied on bulk optics such as mirrors, lenses, and holograms.[2,3] These have been useful research tools but can be limiting to more complex future research activities, and for many applications are not particularly convenient. For most applications, engineers will want to use small, robust components in the form of a photonic integrated circuit (PIC) based on optical waveguides, and may want to achieve complex functions using many optical vortices.

Efforts to integrate OAM optics have been so far limited. One previous example reported by Fontaine and coworkers at Bell Laboratories was a silicon photonic PIC.[4] It splits incoming light equally amongst an array of N waveguides that converge radially towards a concentric circular grating. The grating diffracts the light into emission out of the PIC chip plane. The OAM value—denoted as l and ideally an integer—in the emitted light was controlled by maintaining the correct phase shift ($\Delta\Phi = 2\pi l/\mathrm{N}$) between the arrayed waveguides. The problem is that it is difficult to precisely control $\Delta\Phi$, resulting in a value of l that is not very 'pure' (i.e., not an exact integer). The arrayed waveguides also take up a significant amount of space on the PIC, so that the chip is relatively large. For instance, a single emitter is about 1.5mm × 2mm, so it is not very practical to integrate multiple emitters.



(A) (B) (C)

Figure 1. Microring orbital angular momentum (OAM) emitter with angular grating as seen under scanning electron microscope (A), and the characteristic spiral interference fringes (B and C). The number of arms in the spirals indicates the OAM value.

We have developed a novel approach based on microring resonators that are only a few microns in size and overcome the ambiguity in the OAM value of the emitted light.[5] Our approach allows many devices to be reliably integrated on the same PIC, so that it starts to resemble electronic integrated circuits in which rich functions are achieved by integrating large number of transistors.

A microring resonator traps light in so-called whispering gallery modes (WGMs), first discovered as sound waves echoing around a circular enclosure.[6] Optical WGMs, observable as a series of resonant peaks when sweeping the light wavelength, contain photons with high OAM values as the photons orbit around the enclosed circular cavity. To extract the light from the WGM into a direction essentially vertical to the ring, we also use a grating, but one consisting of periodical features distributed evenly around the 360° azimuthal angle of the ring and hence called an angular grating. The grating has a period similar to the wavelength of the light in the ring and diffracts light out of the ring. Here there is no room for ambiguity in the value of l. The reason is very simple: the light in the WGM can only have an integer number (p) of wavelengths (equaling the optical circumference of the ring divided by the light wavelength λ), the grating must have an integer number (q) of periods, and the emitted OAM

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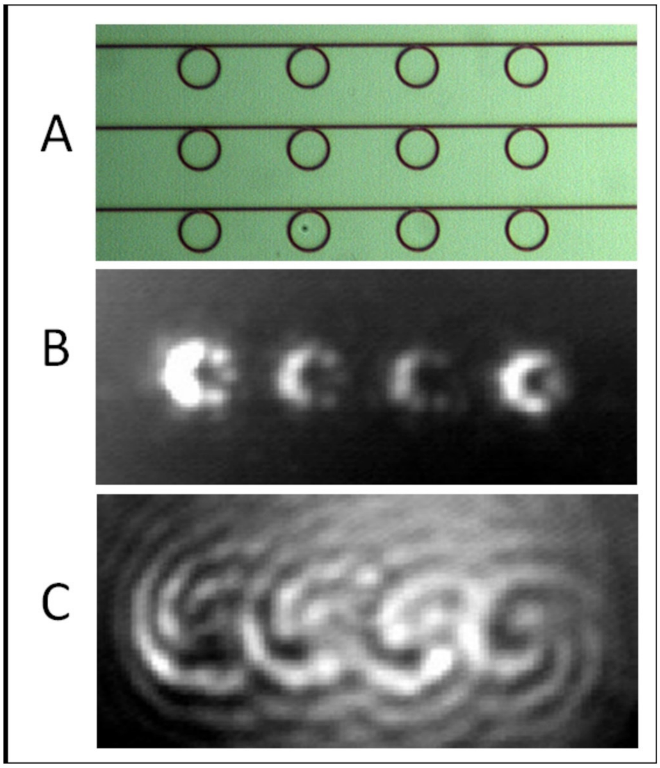

Figure 2. *(A) The micrograph of 4-emitter arrays. (B) The emitted beams from an array. (C) The interference patterns showing the same number of spiral arms. The low resolution in B and C is due to the low magnification used in order to image all four patterns on the camera.*

value is simply $l = p - q$. Furthermore, as a structural parameter q is fixed, but p can be changed by two means: changing the light wavelength or changing the refractive index (n) of the ring material (the optical circumference is geometric circumference multiplied by n). We can, therefore, easily control the OAM value generated by this device.

We made PICs (see Figure 1)—also based on silicon photonic waveguides— consisting of microrings of radii 3.9 and 7.5μm that supported WGMs with $p = 36$ and 72 wavelengths, respectively, at a vacuum wavelength of $\lambda_0 = 1530$nm. We made angular gratings of $q = 36$ and 72 periods in these microrings, therefore expecting them to emit OAM value of $l = 0$ at λ_0 and different l(both positive and negative) values when we changed the wavelength of the light around λ_0, which is coupled into the ring via an access waveguide placed very close ($\sim$200nm) to the ring. When we experimentally measured the OAM values in the beam emitted from the ring by way of interference with a plane wave, we detected positive non-zero integer l values when changing the wavelength to values $<\lambda_0$ (p increases) and vice versa, strictly following the theoretical prediction.

We then proceeded to make PICs that contained multiples of the same devices to demonstrate the potential for integration. We connected identical microring OAM emitters with one shared access waveguide (see Figure 2) and observed exactly the same output OAM values from each ring at each resonance (WGM).

Our work provides a novel approach to integrating very small-sized OAM emitters in large numbers, with exact control of their emitted OAM value. We are now working to make practical applications possible, such as in information technology and manipulation of microscopic particles, by providing robust and highly functional OAM PICs.

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