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A hybrid solution for spatial light modulators with a large space-bandwidth product: opinion

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Abstract: Increasing the space-bandwidth product of spatial light modulators incurs severe issues in terms of power consumption, mutual crosstalk, and control signal wiring. In this opinion article, we propose a novel system to overcome these challenges by marrying energy-efficient modulators in photonic integrated circuits (PICs) and a meta-optical beam aggregator. This hybrid approach can significantly improve the space-bandwidth product, theoretically up to 10^{13} Hz · pixel, which is several orders of magnitude higher than the state-of-the-art.

1. Introduction

Spatial light modulators (SLMs) are cornerstone devices for manipulating the wavefront of free-space light, with many applications including adaptive optics [1], deep tissue imaging [2], light detection and ranging [3], and computer-generated holography [4,5]. A key metric for such SLMs is the space-bandwidth product (SBP), defined as the number of tunable pixels (N^2) times the refresh rate (f_R). We emphasize that a fast modulation rate of a single pixel (f_p) alone does not guarantee a fast refresh rate f_R as the phase profile must be preserved all the time. Either every pixel is controlled simultaneously, necessitating $\sim O(N^2)$ control signals, or pixels are controlled column-by-column using time-division-multiplexing technique. The latter approach is generally used to keep the control signal count tractable at $\sim O(N)$, at the expense of an extra memory element at each pixel. Such memory can be intrinsic to the physical system itself, such as the inertia of liquid crystals (LCs), or provided by external components, such as an electronic latch under each pixel (active matrix). Therefore, $f_R = f_p$ is true only when $\sim O(N^2)$ control signals are used; more often, $f_R = \sim f_p/N$ with $\sim O(N)$ controls using the time-division multiplexing. For commercial LC-based SLMs, the SBP is $\sim 10^8$ Hz · pixel with $\sim 10^6$ pixels and 100 Hz refresh speed. For digital micromirror devices, the SBP is $\sim 10^{10}$ Hz · pixel with $\sim 10^6$ pixels and 10 kHz refresh speed. However, for many applications, such as adaptive optics to image through dynamic disordered media, even higher SBP is required (ideally, $> \sim 10^6$ pixels and MHz to GHz refresh rate) to allow real-time operation.

However, there are multi-layered challenges to increase the SBP. The power needed to operate an SLM is given by:

$$P_{SLM} = \eta E_o N^2 f_R = \eta E_o \cdot SBP$$

where E_o is the switching energy per pixel, and η is the fraction of the pixels that need to be changed between frames. From the equation above, decreasing E_o is necessary to ensure reasonable power consumption when increasing the SBP. Since optical modulation is a volume effect, the reduction of E_o requires lowering the volume of the pixels, which in turn necessitates a large change in the refractive index Δn to achieve a 2π phase shift. Even with unity-order index change ($\Delta n \sim O(1)$), as is possible with non-volatile phase change materials [6] or LCs, the propagation length still needs to be $\sim\lambda$, λ being the free-space wavelength of the light.

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The need for sub-wavelength-scale pixels also comes from the field of view, given by λ^2/Λ^2 (where Λ is the pixel pitch), beyond which aliasing effects would occur [7]. To maintain a large field of view, the pixel pitch needs to be $\sim\lambda$. Therefore, the active volume of the pixel in a large SBP SLM becomes small, $\sim\lambda^3$. Such demand for a smaller active volume has attracted strong interest in creating tunable meta-optics [8,9], where each sub-wavelength meta-atom can potentially be tuned. However, despite years of effort, either global tuning of the entire meta-optics [10–15] or independent tuning of only 1D meta-optics [16–18] has been reported. Modulating each meta-atom in 2D is still lacking because the sub-wavelength pixel pitch poses a serious engineering challenge to routing large numbers of electrical control signals. Obviously, it is physically impossible to have $\sim O(N^2)$ controls for such small pixel pitch. While a crossbar geometry can provide independent control at the expense of a slower refresh rate, carrying high-speed electrical signals on closely placed interconnects would still incur severe heating and crosstalk issues. We note that while such time-multiplexing geometry is the norm in a display, their electrical control signals are of much lower speed (f_R~60 Hz).

Here, we propose a hybrid approach to high SBP by spatially separating the plane of electrical modulation and that of the optical output. This alleviates the routing complexity and reduces the pixel crosstalk. We envision that the electrical modulation is realized using an array of ultra-low energy (sub-fJ/bit) integrated photonic modulators, operating at moderate to high speed (10 MHz ~ 1 GHz). The low power consumption is enabled by the tight confinement of light in integrated photonic waveguides. An electronic integrated circuit (EIC) flip-chip bonded on top of the PIC chip can individually control the modulators. After modulation, light couples out of the chip through a backside-emitting grating coupler array, with each grating coupler functioning as a pixel of the SLM. Although these light beams are far from each other while emitting from the grating coupler array, they can be mapped to a much tighter effective pitch with sub-wavelength spacing using static meta-optics.

2. Decoupling the modulation mechanism from the output pixels

The main limiting factor of the SBP in an SLM is the tightly packed out-coupling pixels and electrical modulation circuits being in the same plane. Although sub-wavelength pixels are preferred for a large field of view and low power consumption, it also poses serious challenges to wiring the control signals, to managing the heat in a small volume, and to resolving the mutual pixel crosstalk. We propose to overcome such limitations by merging the benefits of PICs (ultra-low energy and high-speed modulation) and meta-optics (compact free-space control of light), as shown in Fig. 1(a). We envision that the modulation happens in a PIC via fast tuning mechanisms, taking advantage of many emerging materials, such as graphene [19], lithium niobate [20], indium tin oxide [21], or non-volatile phase change materials [22–24]. The modulated light beams then out-couple with a grating coupler array, which can produce ideal Gaussian [25] or uniform beams [26]. Amplitude modulation can be achieved with critically coupled micro-ring resonators, and phase modulation can be realized using waveguides or highly over-coupled rings [27]. One potential issue is the large pixel pitch, limited by the size of the micro-rings and grating couplers. We assume a ring radius of 5 μm and a grating coupler length of around 10 μm, i.e., a pitch size p = 20 μm. For a 1 inch × 1 inch die, the pixel number is estimated as ≈1270 × 1270, enough for practical applications. More pixels can be achieved by stitching multiple dies [28].

The relatively large pitch size (~20 μm) in Fig. 1(a) restricts the field of view. Moreover, the fill factor of the output is limited due to the grating coupler spacing required for optical routing, leading to discrete dots instead of a continuous wavefront at the output. We overcome these with a bi-layer meta-optical beam aggregator close to the grating couplers, consisting of a metalens (ML) and a metallic aperture (AP). The ML steers and focuses the output of the grating coupler array towards each other at the imaging plane to achieve a smaller pixel pitch. We emphasize

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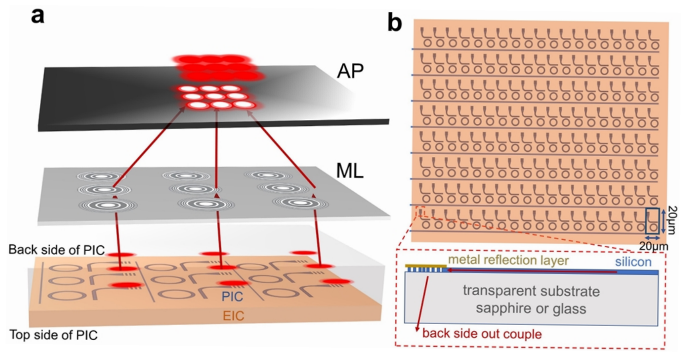

Fig. 1. Proposed high SBP SLM. a Schematic of the proposed SLM, where the modulation happens in a PIC, drawn topside down. An EIC (orange) is flip-chip bonded to the top of the PIC to provide control signals. Meta-optics steer and focus the output beams from the PIC, bringing them closer to achieve sub-wavelength pixels. The beam is then filtered by an aperture array (AP), producing a sub-wavelength pitch beam pattern in the near field. The transmitted light at each hole then functions as a point source, allowing the interaction between pixels to control the wavefront in the far field. **b** Schematic of the proposed PIC. The pitch is estimated as 20 µm. The light couples from the back side with a specially designed grating coupler.

that this ML captures the large pixel-pitch array of beams very close to the PIC plane, before the beams can interfere, and thus precludes any higher order side-lobes. Then, the AP catches the output light spots, each functioning as a Huygens source to allow the interaction between the pixels. Consequently, an output beam pattern can be generated with a high modulation speed, one million pixels, and a sub-wavelength resolution. The flip-chip bonding technique could be used to enable large-scale electrical control, where an EIC is bonded through ball grid arrays on top of the PIC. The EIC will have a crossbar-like structure with an active memory matrix where the size of each memory (e.g., a flip-flop) is ∼10 µm, enabling $O(N)$ control signals. Such a large electronic pitch is well within the range of commercial thin-film transistor active matrix technology, which is typically sub-micrometer, allowing economical processes. As the top EIC will block light, the grating couplers can be designed to collect light from the back side of the PIC with transparent substrate, such as sapphire or glass, shown in the lower panel of Fig. 1(b).

This architecture has several advantages. First, PICs can achieve a high modulation speed of tens, even hundreds of GHz, and a low energy consumption below fJ/bit [20,29]. The latter ensures a small pixel energy E_0, a demanding feature for SLMs with a large SBP. Second, sub-wavelength-scale pixels can be achieved using meta-optics to ensure a large field of view. Each meta-optic can be designed for each output grating to provide the necessary deflection angle. Third, since the modulation location for each pixel is spatially separated from the grating couplers, the mutual crosstalk issue is eliminated. Lastly, the architecture allows more space for control signal routing, significantly relaxing heat management. As such, our scheme could enable $\sim O(N)$ control for a sub-wavelength pixel size, not possible using existing schemes. Moreover, our proposal opens opportunities for $\sim O(N^2)$ independent control in relatively small systems, such as a 100×100 scale, limited by the current EIC. With $\sim O(N)$ controls, $\sim 10^6$ pixels and 10 GHz modulation speed (i.e., 10 MHz refresh rate), our proposed SLM can support an SBP of up to 10^{13} Hz · pixel, orders of magnitude higher than current state-of-the-art.

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3. Experiment

To experimentally demonstrate the idea on a small scale, we designed and fabricated a PIC and a meta-optic focusing layer at 1550 nm. Figure 2(a) shows the image of the PIC with four micro-ring resonators and their output grating couplers. The rings are thermally tunable via metallic microheaters. The PIC is wire bonded to an electrical board to enable independent control of the rings. The meta-optics are designed to steer and focus light from the gratings to the desired final spacing (Fig. 2(b)). In detail, the meta-optic phase profile φ_{MO} consists of a steering phase φ_S plus a lensing phase φ_L, given by

$$\begin{cases} \varphi_S = k \cdot x \cdot \sin(\theta_x) + k \cdot y \cdot \sin(\theta_y) \\ \varphi_L = -k \cdot \left(\sqrt{f^2 + x^2 + y^2} - f\right) \end{cases}$$

where x and y are coordinates on each lens, $k = \frac{2\pi}{\lambda}$ is the wavenumber, θ_x and θ_y are the desired steering angles in the x and y directions, and f is the focal length. The aperture array is not shown here. Figures 2(c) and 2(d) show the beam shape captured by an IR camera before and after the beam aggregator, respectively. The pixel pitch was compressed from 100 μm to ~12.5 μm, where the beams just start to touch each other. Figures 2(e) and 2(f) demonstrate independent amplitude modulation using microheaters.

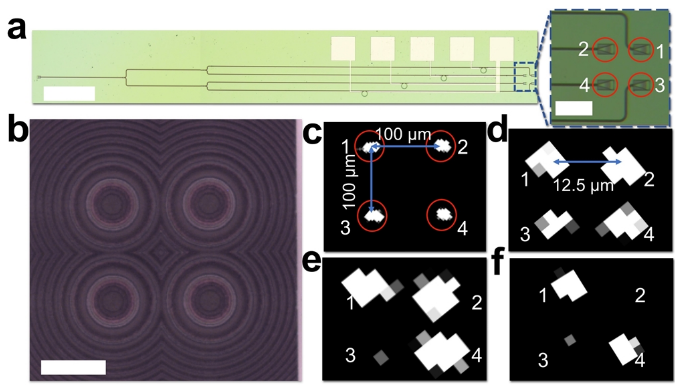

Fig. 2. Preliminary experimental results. **a** The microscope image of a fabricated PIC with four micro-ring resonators and grating couplers. Scale bar: 600 μm. The inset shows the zoomed in image of the grating coupler array. Scale bar: 100 μm. **b** The microscope image of the fabricated meta-optics as a beam aggregator. Scale bar: 50 μm. **c,d** Respectively, measured beam pattern without and with the metalens. The beams are brought closer from 100 μm to ~12.5 μm. **e,f** Respectively, one and two beams are thermal-optically turned off by applying electrical signals to the metallic microheaters. This shows that each pixel can be controlled independently.

4. Conclusion

In conclusion, we propose that the SBP limitation in current commercial SLMs could be eliminated by decoupling the modulation mechanism from the tightly packed out-coupling pixels. Our method could potentially improve the SBP up to 10^{13} Hz · pixel. However, we note that several potential technical problems remain to be addressed. It is non-trivial to design an EIC which operates at GHz rate. In addition, the phase noise from both the PIC and the meta-optical beam aggregator must be characterized and compensated to demonstrate phase modulation.

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Despite these challenges, our proposed method can potentially reach several orders of magnitude higher SBP than existing SLMs.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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