Single-pixel imaging through multimode fiber using silicon optical phased array chip

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Abstract: We experimentally demonstrate single-pixel imaging using a multimode fiber attached with optical phased-array chip. By driving 128 integrated phase shifters, speckle patterns are generated from the fiber to realize clear imaging with 490 resolvable points. © 2020 The Author(s)
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1. Introduction

Due to the capability of supporting a large number of spatial modes within a small diameter, multimode fiber (MMF) is an attractive medium for various imaging applications, such as *in vivo* neural activity observation [1] and ultra-thin endoscopes [2]. In these systems, the single-pixel imaging scheme is commonly applied; the target is illuminated by series of structured patterns through an MMF, and the fluorescence or reflected light is collected by a single-pixel detector. In particular, the use of pseudo-random speckle patterns for illumination offers several advantages, such as enhanced spatial resolution compared with scanning a focused spot [3] and compatibility with the compressed sensing (CS) technique to increase the framerate [4]. On the other hand, bulky spatial light modulator (SLM) is commonly required for switching the illumination patterns, which makes the entire system large, complex, expensive, and slow.

In order to solve these issues, we have recently proposed and numerically demonstrated the use of an optical phased array (OPA) for single-pixel MMF-based imaging [5]. In this work, for the first time, we experimentally demonstrate this concept of imaging through MMF with an integrated OPA to generate pseudo-random speckle illumination patterns. A compact silicon OPA chip with 128 integrated phase shifters is newly developed and attached to an MMF via a 3D-waveguide interface to obtain clear imaging with 490 effective resolvable points. Unlike SLMs, which operate commonly at few kHz or slower, the integrated OPA potentially offers a substantially higher operating bandwidth beyond 100 MHz [6]. Furthermore, CMOS driver circuit and photodetector can also be integrated on the same silicon chip to realize ultimately compact and low-cost system.

2. Imaging scheme using multimode fiber and integrated optical phased array

Figure 1 shows the schematic of single-pixel imaging using an OPA chip and MMF. In the OPA, input light is split to N waveguides by a $1\times N$ splitter, and phase-controlled by N independent phase shifters attached to respective waveguides. The output light from the OPA is coupled to a glass-based 3D waveguide chip (3D-WG) [7], in which the N waveguides are rearranged from 1D array to 2D array and coupled to the MMF. The target is placed in vicinity of the MMF output, so that it is illuminated by the near-field pattern (NFP) from the MMF. The optical power transmitted through the target is collected and detected by a single-pixel photodetector. In this work, we used the transmitted light for convenience, but the reflected light could also be used for practical applications.

By driving N phase shifters on OPA, we can generate K different wavefront patterns at the output of OPA [8], which are then converted to 2D illumination patterns $\mathbf{I}_k$ (k = 1, 2, …, K) by transmitting through the 3D-WG and MMF [5]. For each pattern, transmitted optical power S_k through the target is recorded. The image $\mathbf{O}$ of the target can then be

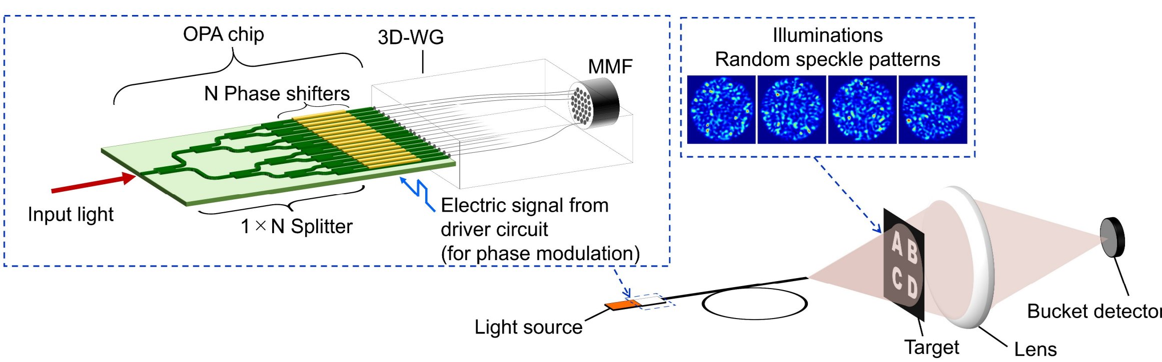

Fig. 1. Schematic of single-pixel imaging using MMF and OPA.

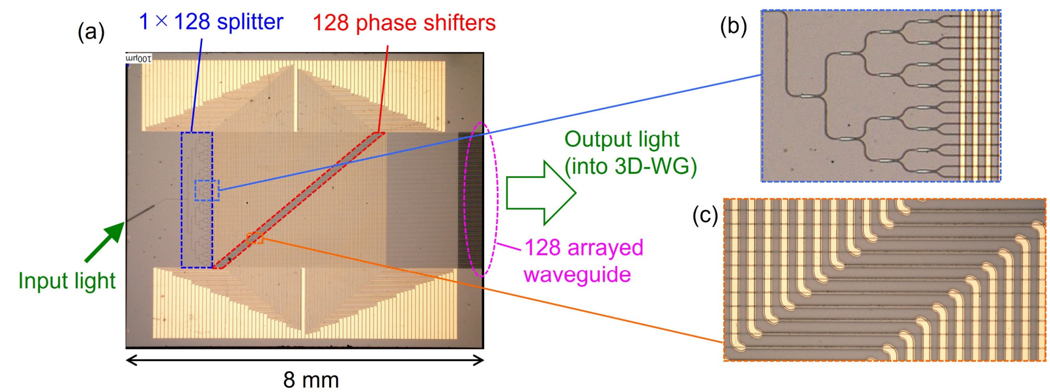

Fig. 2. Microphotograph of the fabricated OPA chip. (a) Overall view. (b) 1×2 MMI couplers. (c) TO phase shifters.

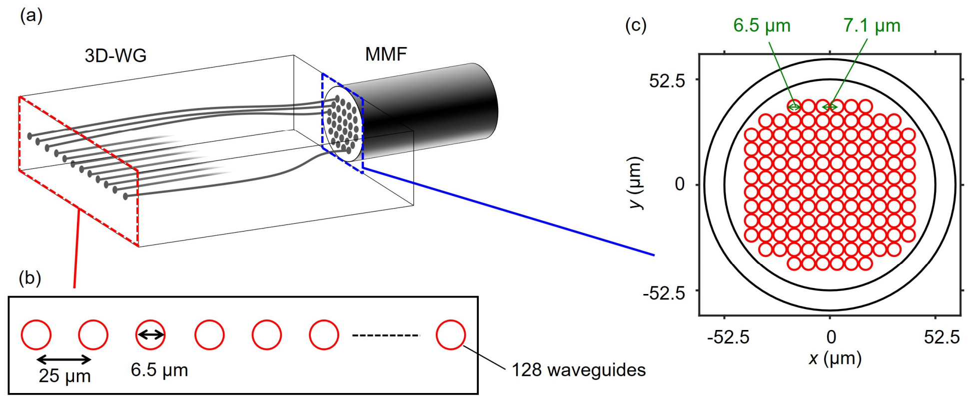

Fig. 3. Schematic of the 3D-WG. (a) Overview of the chip. (b) Input facet (connected to output of OPA).
(c) Output facet (connected to input of MMF)

reconstructed as $\mathbf{O} = \mathbf{I}^{+}\mathbf{S}$ [3], where $\mathbf{I} = [\mathbf{I}_1, \mathbf{I}_2, \ldots, \mathbf{I}_K]^{\mathrm{T}}$ is a matrix representing the illumination patterns, $\mathbf{S} = [S_1, S_2, \ldots S_K]^{\mathrm{T}}$, and $\mathbf{I}^{+}$ denotes the Moore-Penrose generalized inversion matrix of $\mathbf{I}$. Note that once the matrix $\mathbf{I}^{+}$ is acquired before the measurement, reconstruction is a simple and fast matrix multiplication. We should also note that since a well-shaped focused beam is not required, precise phase calibration and optimization of OPA are unnecessary, which enables relatively robust imaging [8].

3. Device structure and experimental setup

Figure 2 shows the microphotograph of the OPA chip with 128 phase shifters (N = 128), fabricated on a silicon-on-insulator (SOI) wafer with 220-nm-thick silicon layer and 3-μm-thick buried oxide (BOX) layer. The waveguide width was set to be 400 nm to ensure single-mode operation. The input light was equally distributed to 128 waveguides by cascaded 1×2 multimode interference (MMI) couplers [Fig. 2(b)]. Although carrier-effect-based or electro-optic-effect-based phase shifters could be used to enable high-speed switching beyond 100 MHz [6], for simplicity in this work, we employed 250-μm-long thermo-optic (TO) phase shifters with Ta heaters [Fig. 2(c)].

Figure 3 shows the schematic of 3D-WG, where 128 waveguides with a mode-field-diameter (MFD) of 6.5 μm were formed inside a glass chip using a focused short-pulse laser beam [7]. A 1D array with a waveguide pitch of 25 μm at the input was converted to a 2D array with a pitch of 7.1 μm at the output of 3D-WG. A standard step-index MMF (Thorlabs M43L02) with core diameter of 105 μm, NA of 0.22, and length of 2 m was directly attached at the output of 3D-WG.

Figure 4 shows the experimental setup. A continuous-wave (CW) light was amplified using an erbium-doped fiber amplifier (EDFA), aligned to the transverse-electric (TE) mode using a polarization controller (PC), and coupled into the OPA chip via a lensed fiber. The NFP of the MMF was magnified by approximately 70 times using two cascaded 4-f systems to illuminate a circular area with a diameter of 7.06 mm. For the ease of experiment, the illumination pattern was monitored by inserting a beam splitter (BS) and using an InGaAs camera. In the image reconstruction, we

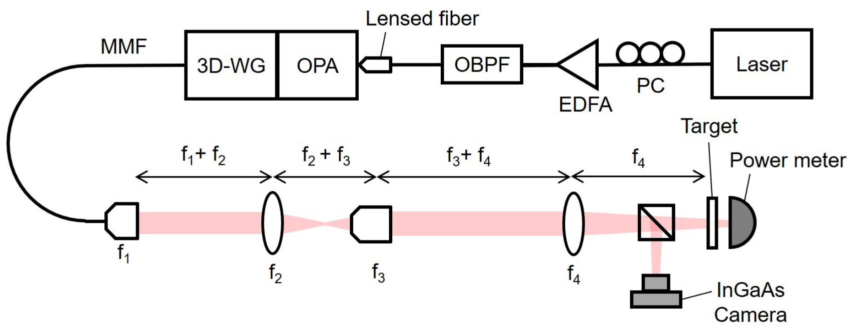

Fig. 4. Experimental setup. f_1 = 6.2 mm, f_2 = 20 mm, f_3 = 3.6 mm, f_4 = 75 mm. OBPF: optical band pass filter.

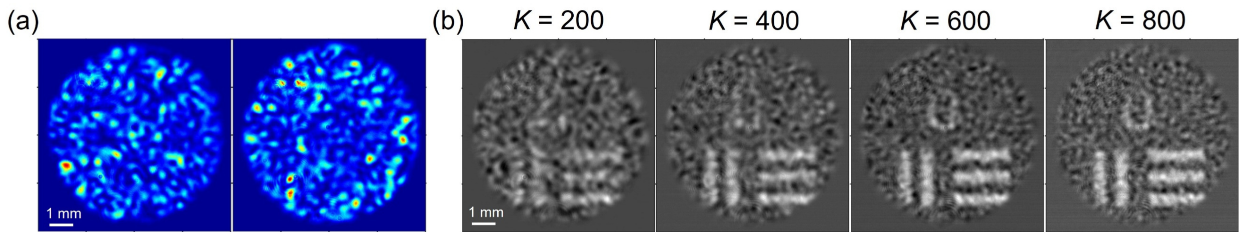

Fig. 5. Experiment results. (a) Examples of acquired random speckle illumination patterns.
(b) Image reconstruction result. *K*: number of switched patterns

used truncated singular value decomposition for acquiring the inverse matrix to avoid enhancement of undesired noise elements.

4. Experimental result

Figure 5(a) shows two examples of generated NFP at the MMF output measured when different sets of driving voltage are applied to the phase shifters. We can see that random speckle patterns are generated and modulated over the entire core of the MMF. Figure 5(b) shows the results of imaging 1951 USAF resolution target (group 0, element 2). By using sufficient number of illumination patterns ($K \geq 600$), a fine image of the target with 0.45-mm-wide stripes is obtained. From the point-spread function analysis based on the measured data [3], the effective number of resolvable points is derived to be 490, which is much larger than the number of phase shifters ($N = 128$). While the framerate was limited by the slow TO phase shifters in this work, high-speed imaging over 100 MHz should be possible by using carrier-effect-based or electro-optic-effect-based phase shifters [6].

5. Conclusion

We have experimentally demonstrated single-pixel imaging through an MMF with an integrated OPA chip for the first time. Instead of employing bulky SLM for wavefront modulation, a compact OPA with 128 integrated phase shifters was used to generate 2D speckle patterns at the MMF output, which enabled clear imaging of the target with 490 resolvable points. Since the silicon-based phase modulators can potentially operate at an ultrahigh-speed rate exceeding 50 GHz [9], demonstrated scheme paves the way towards low-cost, ultra-compact, and high-speed imaging system through MMF, which has wide applications in the field of *in vivo* imaging and ultra-thin endoscopes.

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