On-Chip 4f-System-Based Arbitrary-Mode Spot Size Conversion

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Abstract *An on-chip spot size converter is proposed and demonstrated for arbitrary modes, using a pair of lenses in a 4-f imaging system configuration. The device length can be reduced by 72% compared to linear taper at a same inter-mode crosstalk level.*

Introduction

Spot size conversion is a key functionality to manipulate the mode dimension for the requirements both in intra-chip and on/off-chip scenarios. For years, spot size converters (SSCs) for fundamental mode have been thoroughly investigated, based on adiabatic taper, non-adiabatic taper, transformation optics, and single-lens-assisted taper[1]-[5]. For high-order modes, spot size conversion is also desired to connect the multi-mode integrated devices with different waveguide widths[6], and to couple few-mode fiber to chip[7]. These structures rely on the adiabatic mode evolution, and lack for compactness and/or compatibility with fundamental mode. The footprint could be improved by using non-adiabatic taper or transformation-optics-based scheme, at the cost of extra optimization or fabrication difficulty. Having been proposed for fundamental transverse electric (TE_0) and first-order transverse electric (TE_1) modes[4],[5],[8], single-lens-assisted tapers are compact whereas difficult to accommodate higher-order modes. In these structures, the Fourier transform (FT) property of the lens determines that the output mode profile is in the form of spatial frequency spectrum. This would lead to the shape distortion when this spectrum is in a different shape from input profile. In addition to regular modes (fundamental and high-order modes), spot size conversion for irregular modes is also essential in the cases such as the measurement of an on-chip diffractive computing system[5], and a wider mode profile is very helpful to improve the spatial resolution. To the best of our knowledge, on-chip SSCs working for irregular modes have not been demonstrated. To sum up, a compact SSC for arbitrary modes is highly desired.

In this work, we propose and demonstrate a 4f-system-based SSC (4f-SSC) for arbitrary-mode spot size conversion on the silicon-on-insulator (SOI) platform. The proposed device can be regarded as an analogy of the beam expander in bulk optics, and the 4-f imaging system configuration enables the compatibility with arbitrary modes. It is designed to widen an arbitrary-profile mode from 8 to 20 μm with a 168 μm device length. Both regular and irregular modes are numerically studied with TE polarization. Regular modes are experimentally demonstrated with low inter-mode crosstalk.

Design and analysis

Beam expander is broadly adopted in free-space optical systems to collimate laser beam, and it can be assembled in a configuration of Keplerian telescope, as shown in Fig. 1(a). Two focusing lenses with focal lengths of f_1 and f_2 are placed at a distance of f_1+f_2. In this scenario, an incident beam with a diameter D_i is transformed into an output beam with a widened diameter D_o, and the expansion ratio can be expressed as $D_o/D_i = f_2/f_1$[9]. Here, we propose a 4f-SSC on the SOI wafer (Fig. 1(b)), using two on-chip lenses (C-Lens1 and C-Lens2) with focal lengths of f_{c1} and f_{c2}. For clarity, the SiO_2 top cladding is not displayed. In order to intrinsically preserve the mode profile shape, a 4-f imaging system configuration is used. The output mode profile is an “image” of the input one, and this guarantees

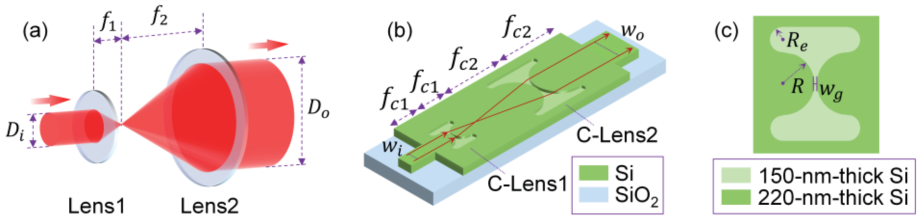

Fig. 1: Schematic of the proposed 4f-SSC. (a) Beam expander in bulk optics. (b) On-chip 4f-SSC. (c) On-chip lens.

little shape distortion. According to the FT analysis, for an input mode profile $E_i(y)$ with width w_i, the output mode profile is given by

$$E_o(y) \propto E_i(-\frac{f_{c1}}{f_{c2}}y) \quad (1)$$

Compared to the input mode profile, the output one is spatially reversed, and its width w_o is widened by a ratio $M = f_{c2}/f_{c1}$, without changing the profile shape $E_i(y)$.

Defined on a wafer with a 220 nm top silicon layer, the on-chip lens is a symmetrical structure with 150-nm-thick silicon, as shown in Fig. 1(c). The structure contains two semicircles with radius R, spaced with a gap width w_g = 200 nm. For fabrication feasibility, semicircles with radius R_c = 2.5 μm are added at four corners of the lens to remove the sharp angles. The focal length can be estimated by

$$f = \frac{n_2 R}{2(n_2 - n_1)} = kR \quad (2)$$

where n_1 = 2.54 and n_2 = 2.848 are the effective indices of the 150-nm-thick and the 220-nm-thick silicon slabs at 1550 nm, respectively. Thus, f is proportional to R, with a constant coefficient denoted by $k = n_2/[2(n_2-n_1)] \approx 4.6$. The exact value is obtained to be k = 4 by optimizing the transmittance of a 4-f system with two identical lenses, using 3D finite difference time domain (FDTD) method.

With the configuration mentioned above, a 4f-SSC is designed, and the input and output mode widths (w_i and w_o) are set to be 8 and 20 μm, respectively. The radius R for C-Lens1 is chosen to be 6 μm to make the aperture slightly bigger than w_i. By applying Eq. (2), its focal length is f_{c1} = 24 μm. Then, the focal length for C-Lens2 (f_{c2}) is determined to be 60 μm, because the expansion ratio M ought to be $f_{c2}/f_{c1} = w_o/w_i$ = 2.5. Accordingly, the R for C-Lens2 is calculated to be 15 μm.

The performance of the 4f-SSC is numerically investigated. Figure 2(a) illustrates the light propagation in the device for second-order transverse electric (TE_2) mode and irregular mode with asymmetrical profile. The widths of the two modes are 8 μm at the input port, and they are widened to 20 μm at the output port. For each mode, the input and output mode profiles have same shapes. It is worth noting that the output profile is reversed according to Eq. (1).

According to the calculated transmission results, the insertion loss for TE_2 and irregular modes are 1.15 and 0.8 dB, respectively. The loss is mainly introduced by the lenses, as the index contrast causes scattering loss, and a tiny part of light is not effectually focused, escaping from the 4-f system. The inter-mode crosstalk values from TE_2 to TE_0 and TE_1 modes are all <-25 dB.

For comparison, as shown in Fig. 2(b), a single-lens SSC (SL-SSC) is also considered for 8-μm-wide incident modes. The lens named C-Lens2 is identical to the one in the 4f-SSC. Similar to the single-lens assisted taper design[4], the distance between the port with narrow mode width and the C-Lens2 is set to be f_{c2}. For each mode, when propagating through the lens, the mode profile shape is not preserved because of the lens's FT property. The shape of the spatial FT result is different from the input mode profile.

On the other hand, the spot size conversion for regular modes can also be performed using adiabatic tapers. For a linear taper to perform expansion from 8 to 20 μm, simulation indicates that at least ~600 μm length is needed to achieve <-25 dB inter-mode crosstalk, for TE_2 mode. By contrast, the proposed device length is 168 μm, which is 28% of the linear taper.

Fabrication and characterization

The proposed 4f-SSC was fabricated on an SOI wafer with a 220 nm top silicon layer, using deep ultraviolet lithography and inductively coupled plasma etching. A 2 μm SiO_2 layer was deposited as top cladding. The optical microscope image of fabricated device is shown in Fig. 3(a). A pair of mode (de)multiplexers ((de)MUXers) is used to characterize the performance for regular modes. For TE_0, TE_1 and TE_2 modes, the ports are defined as I_0, I_1 and I_2 on the input side, and O_0, O_1 and O_2 on

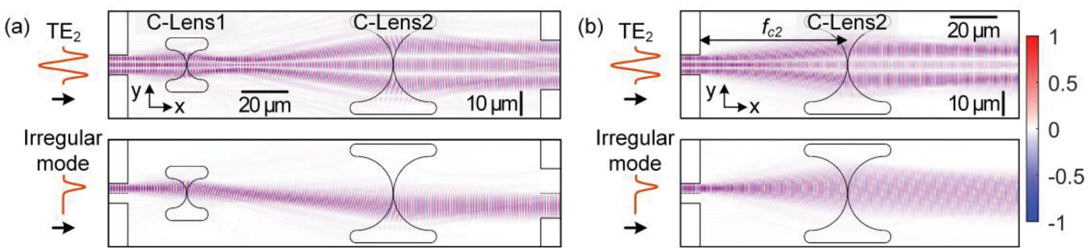

Fig. 2: Simulated light propagation profiles (E_y) in the (a) 4f-SSC and the (b) SL-SSC for TE_2 and irregular modes.

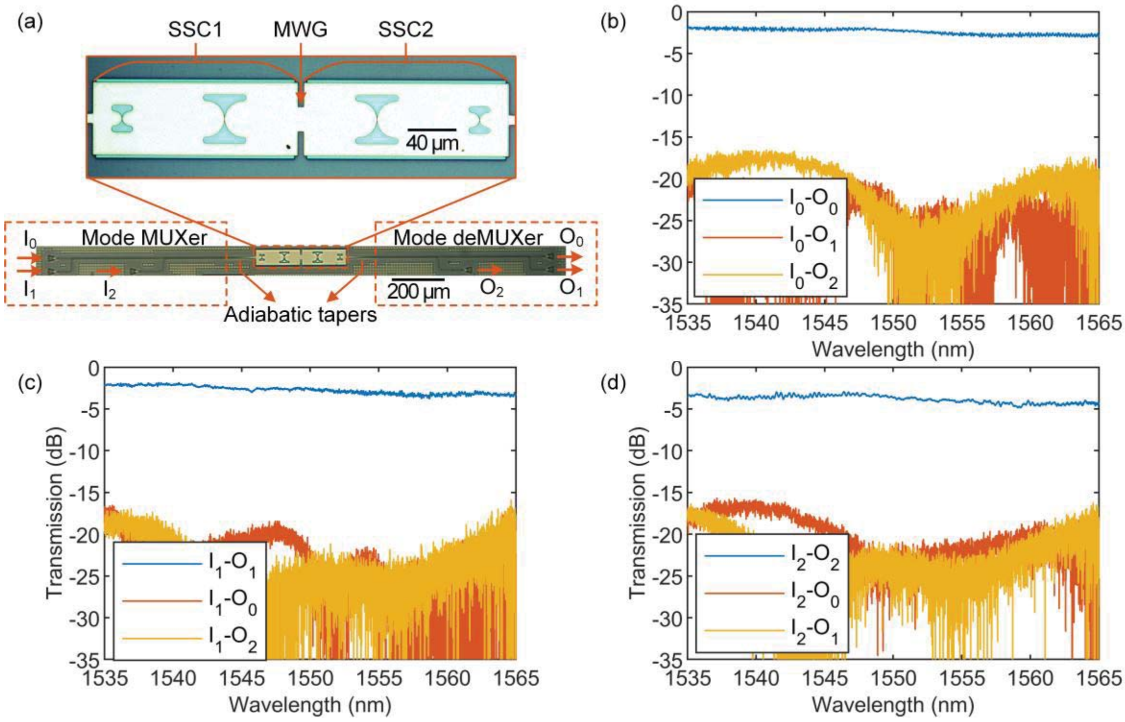

Fig. 3: (a) Optical microscope image of the fabricated device with a detailed view of cascaded 4f-SSCs shown as inset. Measured transmission spectra when light inputting from port (a) I_0, (b) I_1 and (c) I_2.

the output side. As illustrated in the inset, two 4f-SSCs (SSC1 and SSC2) are cascaded in mirror symmetry. They are connected with a 20-μm-wide multimode waveguide (MWG) to validate the widened mode width is 20 μm, considering that any mode mismatch would lead to inter-mode crosstalk. The waveguide width transitions between mode (de)MUXer and 4f-SSC are achieved by adiabatic tapers. In addition, a reference mode multiplexing link is also fabricated for loss normalization.

The measured transmission spectra are presented in Figs. 3(b), 3(c), and 3(d). The "I_0-O_0" denotes the transmission from port I_0 to port O_0. The spectra are normalized by subtracting the loss of mode (de)MUXers. Considering the cascaded devices, the insertion losses at 1550 nm are 1.07, 1.28 and 1.82 dB for TE_0, TE_1 and TE_2 modes, respectively. The slightly larger measured value may result from the sidewall roughness in the etching. The inter-mode crosstalk values are <-17 dB at 1550 nm.

Conclusion

We have proposed and demonstrated an on-chip 4f-SSC for arbitrary-mode spot size conversion. In analogy with beam expander in bulk optics, the 4f-SSC consists of two lenses in a 4-f imaging system configuration, enabling the widening of an arbitrary mode from 8 to 20 μm while preserving its shape. The device length is only 28% of the linear taper at a same inter-mode crosstalk level. For TE_0, TE_1 and TE_2 modes, the experimental results show reasonable insertion losses (<1.82 dB) and low inter-mode crosstalk (<-17 dB).

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