# Structured Illumination Chip Based on Integrated Optics *

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*A compact structured illumination chip based on integrated optics is proposed and fabricated on a silicon-on-insulator platform. Based on the simulation of Gaussian beam interference, we adopt a chirped diffraction grating to achieve a specific interference pattern. The experimental results match well with the simulations. The portability and flexibility of the structured illumination chip can be increased greatly through horizontal encapsulation. High levels of integration, compared with the conventional structured illumination approach, make this chip very compact, with a footprint of only around 1 mm$^2$. The chip has no optical lenses and can be easily combined with a microfluidic system. These properties would make the chip very suitable for portable 3D scanner and compact super-resolution microscopy applications.*

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Structured illumination (SI) is the process of projecting a known pattern (such as a grid) onto a particular object or plane. It has been widely used in 3D scanners,[1] whereby these patterns deform upon striking a surface and thus allow a vision system to calculate the depth and surface information of the object. Structured light illumination was first introduced by Neil *et al.*[2] in 1997 who applied it to an optical section for biological imaging. In recent years, there has been an increasing interest in structured illumination microscopy (SIM), in which it can increase the lateral resolution by a factor of 2.[3] When using nonlinear phenomena, theoretically, it can improve the resolution infinitely.[4]

Rapid developments in both 3D scanners and SIM technology have heightened the need for high-frequency and high-contrast structured illumination patterns. As we know, the interference between two or more laser beams can constitute one-, two-, or three-dimensional structured light patterns, respectively.[5,6] Conventional beamsplitters and gratings,[2] or even a simple illumination mask placed in the path of the light, can be used to divide or diffract an incident beam into two or multiple coherent beams. Nevertheless, in these approaches, mechanical stability is an important factor, due to the fact that the relative length of the two beam paths formed by the beamsplitters must remain stable with a sub-wavelength degree of precision for the duration needed to record an entire set of images. The mechanically slow movement limits the imaging speed and may lead to fluorescence photo-bleaching and phototoxicity. Another widely used method for generating the structured illumination is the spatial light modulator (SLM), which is an object that imposes some form of spatially varying modulation on a beam of light. There are a few types of SLMs on the market, such as the liquid-crystal SLM, digital micromirror devices (DMD),[7] and liquid-crystal on silicon (LCOS) devices.[8] These devices can create flexible structured illumination patterns with high-speed phase-shifting and fringe orientation rotation. However, they are hindered by complex optical paths, the requirement of a large amount of space, and high consumption. A DMD is a two-dimensional reflection-diffraction grating, with which the optical path will become more complicated when the light source is a laser.

In this Letter, a novel silicon-on-insulator (SOI) chip that can provide structured illumination based on integrated optics is proposed, and its fabrication and characteristics are described. SOI is an interesting and promising material for high-density photonic integrated circuits due to its high refractive-index contrast as well as its intrinsic compatibility with a complementary metal-oxide semiconductor (CMOS).[9] Through careful design of the input and output coupled gratings, we are able to fabricate a compact, easily configured, integrated chip. These properties are promising for applications in future highly compact 3D scanners and SIMs.

Since the fundamental (or TEM00) transverse Gaussian mode describes the intended output of most lasers, as a starting point, we simulate the interference of two and three Gaussian beams using finite difference time domain (FDTD) software at an operating of the projections of all three vectors, separated by exactly 120° in the $x$–$y$ plane. The parameter that defines each Gaussian beam is the same, with $\lambda_0 = 1.6\,\mu\text{m}$, $\omega_0 = 18\,\mu\text{m}$, $z = 80\,\mu\text{m}$, $\theta = 10°$ and $r = 27\,\mu\text{m}$, where $\lambda_0$ is the free-space wavelength, $\omega_0$

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is the waist size, $z$ is the axial distance from the two or three beams' focus, and $r$ is the radius from the central axis of the beam.

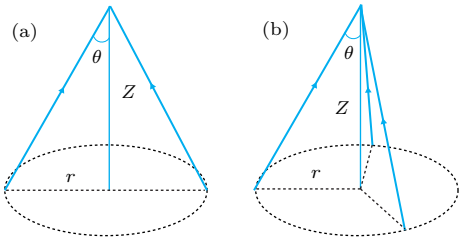


**Fig. 1.** (a) Optical arrangement of two-beam and (b) three-beam interference. Each beam is symmetrically oriented around the vertical axis by angle $\theta$, $r$ is the radius of the circle comprising the incident beam array, and $z$ is the axial distance from the center of the circle.

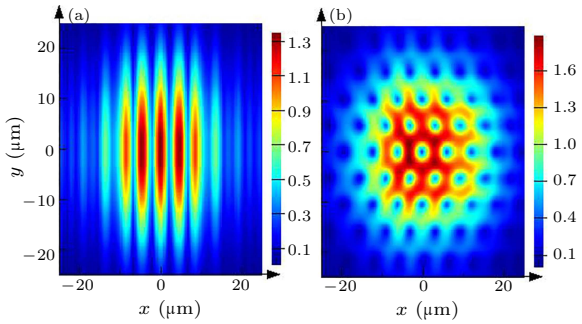


**Fig. 2.** (a) FDTD simulation of two Gaussian beam interferometers, and (b) FDTD simulation of three Gaussian beam interferometers. Here $\lambda_0 = 1.6\,\mu\text{m}$, $\omega_0 = 18\,\mu\text{m}$, $z = 80\,\mu\text{m}$ and $\theta = 10°$.

The results of the simulation are shown in Fig. 2, where red color corresponds to high intensity and blue color corresponds to low intensity. Figure 2(a) is the interference simulation diagram for two Gaussian beams. It generates a one-dimensional sinusoidal fringe pattern. The periodicity of the interference pattern depends on the angle and the laser wavelength, and is given by

$$T = \lambda_0/(2\sin\theta). \tag{1}$$

According to the simulation, the interference intensity distribution along the $x$-axis is a sine curve. After the application of the fast Fourier transformation (FFT), we obtain a stripe period $T = 4.41\,\mu\text{m}$. Figure 2(b) is the interference simulation pattern for three Gaussian beams. As can be seen, a hexagonal pattern is formed. The periodicity or lattice constant, $P$, of the resulting interference pattern is determined by[10]

$$P = (2\lambda_0)/(3\sin\theta). \tag{2}$$

The simulation result is $P = 6.08\,\mu\text{m}$. Equations (1) and (2) are related to the plane waves and are therefore not ideal for applications in our experiments due to the fact that we have used the Gaussian wave. We decide to use these equations due to the fact that, in our case, the Gaussian wave can be similar to the plane wave.

By utilizing a grating coupler (GC), light can be injected anywhere on the surface of an optical circuit.[11] Compared with the traditional method, there is no need to polish the facets, it has good alignment tolerance, and can be used for wafer-scale optical testing. According to the results of the simulation, and by drawing on the results of our previous work,[12] we propose a novel SOI chip based on integrated photonics that can generate structure light. We use a GC to pass light through an optical fiber to the optical waveguide. With a beamsplitter, light could be divided into two or three beams. Instead, by using the output GC, the light from the optical waveguide is diffracted into air, thus forming a specific interference pattern.

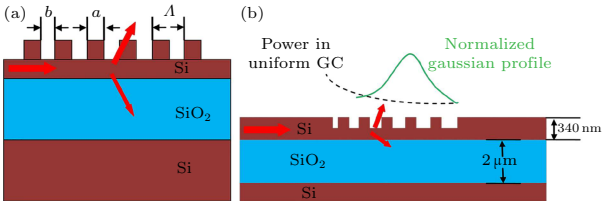


**Fig. 3.** (a) Crossing section of the designed grating structure. (b) The schematic picture of a chirped GC.

The basic grating structure is a periodic structure with a finite number of rectangular teeth. The period for vertical out-of-plane coupling is given as

$$\Lambda = \lambda/n_{\text{eff}}. \tag{3}$$

In general, the effective refractive index $n_{\text{eff}}$ of the grating is a function of the grating parameters, $\Lambda$ is the period of the grating shown in Fig. 3(a), and $\alpha$ is the width of each tooth of the grating shown in Fig. 3.(a). In a first-order approximation, the field diffracted from a uniform grating structure decays exponentially along the propagation direction of the light (see Fig. 3(b)). An improvement in the fiber coupling efficiency can be obtained by using non-uniform diffraction gratings to better match the diffracted field profile to that of the Gaussian fiber mode.

In this study, non-uniform gratings are used as the input and two or three output grating couplers. Details on the grating design can be found in Ref. [12]. A light beam is injected into the grating coupler with a small off-vertical tilt of 10° (see Fig. 4(b)) to reduce the large second-order back reflection. The light coupled into the waveguide is divided by an optical waveguide beam splitter into two or three beams, and the light is then emitted through the GCs. As a result, the output light beams of specific angles interfere and we can observe the interference fringe.

The proposed SOI chip, which can provide structured illumination based on integrated optics, is fabricated on a silicon-on-insulator wafer with a 340-nm top silicon layer and a 2-μm buried oxide layer. EBL and inductively coupled plasma etching are utilized to define and etch the waveguides. We select an etch

depth of 198 nm which has been shown to be most appropriate.[12]

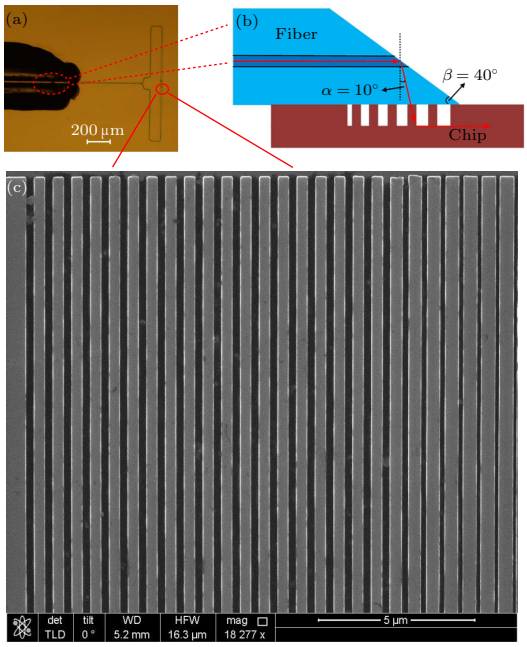


**Fig. 4.** (a) Microscope image of the configuration of the two gratings. The red-dotted-line circle region corresponding to the input is enlarged in Fig. 4(b), and the output is enlarged in Fig. 4(c). (b) Encapsulation of the optical fiber and input grating. (c) SEM images of the fabricated output grating.

After the completion of the coupler grating fabrication, we need to test and evaluate the main properties of the proposed chip. We characterize the SI chip performance by horizontally coupling a tunable light source (AQ2200-136, Yokogawa) into the silicon waveguides using corner-cut single mode fibers, as shown in Fig. 4(b). A polarization controller is used to ensure a TE mode input. The output signal is monitored by using a fiber-optic power meter (FOT-90 A, EXFO). The position of the fiber is adjusted to minimize the loss, after which UV curing glue is used to couple the optical fiber to the designed input GC. The microscope image of the two gratings shown in Fig. 4(a) gives a perspective of the fabricated chip. The red circled region shown in Fig. 4(a) is enlarged in Figs. 4(b) and 4(c). Figure 4(b) shows the optical fiber and the input grating coupler. Figure 4(c) is a scanning electron microscope (SEM) view of the diffraction grating. As can be seen from the scale shown in Fig. 4(a), the proposed SI chip has a compact footprint of around 1 $mm^2$.

After the SI chip was packaged, it was placed under 1× (see Figs. 5(b) and 5(e)) and 5× (see Figs. 5(c), 5(d), 5(g) and 5(h)) objective lenses with a 0.7–4.5× zoom lens. A C-mount adapter enables the use of these lenses with an infrared camera (Hamamatsu C10633-23) with a resolution of 320 × 256. Figure 5(a) is the SI chip layout. As shown in Fig. 5(b), 1, 2, and 3 are the light leakage spots formed due to the bending of the optical waveguide. The scale bar in Fig. 5(b) can be obtained by comparing the inputs and outputs of Fig. 5(b) with those of Fig. 5(a), the scale bar is known. Due to the limitations of the manufacturing process, grating couplers will differ very slightly from the intended design, leading to an output wavelength shift. As shown in Fig. 5(b), the two-output intensities are not the same at the designed wavelength. Therefore, we measure the test structures shown in Fig. 4(a) by changing the wavelength from 1480 nm to 1650 nm in steps of 1 nm to find the wavelength at which the two output ports have the same output. Due to the fact that the two-output light intensities are nearly the same at wavelength 1600 nm, thus it is adopted, as shown in Figs. 5(c) and 5(g).

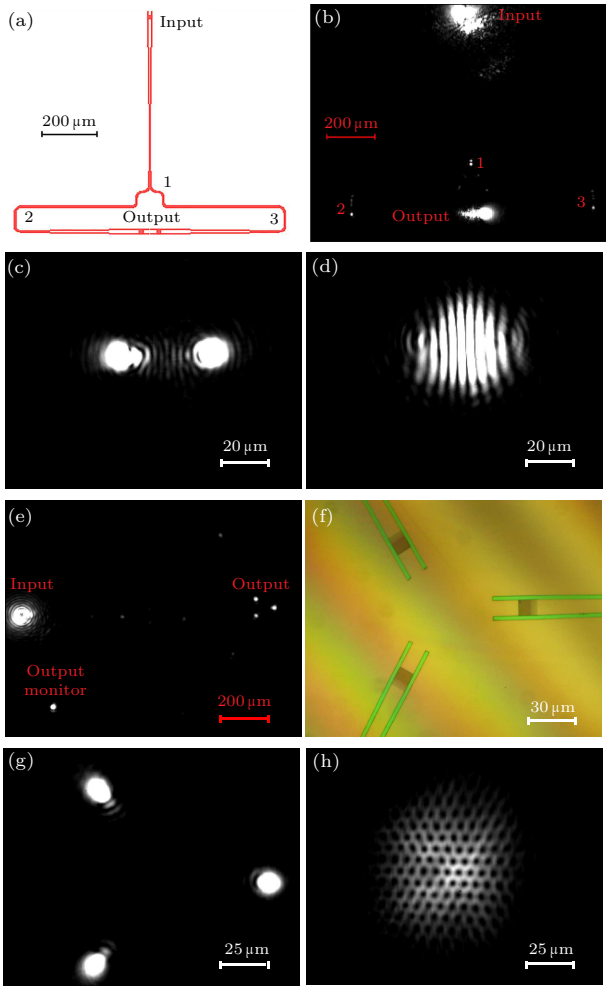


**Fig. 5.** (a) Design layout of the two-Gaussian beam SI chip. Here 1, 2, and 3 are the bend waveguides. (b) Image of the two-Gaussian beam SI chip under 1× magnification. It is observed that the light leakage spots at 1, 2, and 3 are formed due to the bending of the optical waveguide. (c) Minimum beam spot with two interfering beams. (d) Interference between two Gaussian beams at $z = 80\,\mu m$. (e) Image of the three-Gaussian beam SI chip under 1× magnification. (f) Microscope image of the three gratings under 50× objective. (g) Minimum beam spot when three beams interfere. (h) Interference of three Gaussian beams at $z = 80\,\mu m$.

After adjusting the focal length $z$, we could easily obtain the interference as shown in visualization 1

(two beams) and visualization 2 (three beams). By changing the value of $z$ in steps of 1 μm, we defined $z$ as being zero when the minimum-sized beam spot is attained. The two beams interfere at $z = 80\,\mu\text{m}$, as shown in Fig. 5(d). To perform the simulation, we draw a straight line along the $x$ axis of Fig. 5(d). After the FFT, we obtain the stripe period. Figure 5(h) is the interference diagram for three Gaussian beams when $z = 80\,\mu\text{m}$. As can be seen, a honeycomb-like structure pattern is acquired at $P = 6.57\,\mu\text{m}$.

In conclusion, the design, fabrication, and characterization of a novel structured illumination chip based on integrated photonics have been presented. Through simulation of Gaussian beam interference, we obtain the period of the interference fringe. The SOI material is adopted to design the diffraction grating, and a chirped GC is used to produce an output light beam with a Gaussian distribution. By encapsulating, light coupled into the designed SI chip through the corner-cut single-mode fiber, the interference experiment results are obtained. The experimental results are in good agreement with the simulations.

Compared with the popular SI approach, high level of integration makes this chip very compact and inexpensive, having a footprint of only around $1\,\text{mm}^2$. The chip has no optical lenses and it is easy to combine with a microfluidic system. Although the chip is based on the SOI material, the working wavelength is in the infrared range; after changing the material, for instance silicon nitride, a visible-wavelength SI can be acquired. The period of the pattern could also be significantly reduced by changing the angle in Eqs. (1) and (2). Obviously, to achieve a complete application of structured-light super-resolution imaging, more grating coupler arrays, optical switches, and optical phase shifters would be essential. With those components, it can flexibly control the patterns in high spatial frequency, precise phase-shifting, orientation rotation. These properties are promising for applications to future portable 3D scanners and compact super-resolution SIM applications.

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