UV Photonic integrated Circuits for Structured Illumination Microscopy with High Optical Throughput

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Photonic integrated circuits (PICs) have the potential to upgrade the performances of standard optical microscopes. We have recently shown that PICs operating in the UV wavelength range enable label-free structured illumination microscopy (SIM) in a compact and robust way for biological imaging cells with improved spatial resolution. The state of the art for the field of view (FoV) of UV PICs-based SIM is currently 150 µm × 200 µm. This has been achieved by using a conventional imaging microscope objective, the numerical aperture of which was 0.5. The FoV is not limited by the imaging path but by the illumination, i.e. by the PIC design. Although a two-times resolution improvement is achieved, only a small fraction of the 1mm×1mm FoV offered by the objective, is used. Consequently, the optical throughput of the microscope is considerably limited, which hinders biological studies requiring the imaging of a large number of cells at the same time. To benefit from the maximum optical throughput, we present here a grating design for off-chip illumination at a wavelength of 360 nm with an 800 µm length. With a 2 nm shallow etched grating made of 5000 periods and patterned on an aluminum oxide waveguide, the FoV length is increased by four times.

Introduction

The bio-optical imaging never lowered the demand for obtaining massive information through a low-cost and compact imaging system. Having high information content requires the system to have a high optical throughput [1]. This is determined by the optical system's NA and field of view which can be represented as the étendue G-value. Limited by the optical diffraction, the performance of the conventional optic lens cannot break the trade-off between the NA and field of view. The G-value of the conventional objective lens is indeed bound between 0.0243 to 0.9503 [2]. Nowadays, many technologies can be applied to acquire both high NA and high field of view [1]. As a super-resolution imaging technique, structured illumination microscopy can increase the imaging resolution by a factor of two without sacrificing the field of view. This method is implemented by illuminating the object with a fringe pattern to shift high spatial frequencies of the object into the pupil of the microscope and consequently enhance the spatial resolution of the image. The key component to generate the structured illumination is generally, a spatial light modulator (SLM), or a digital micromirror device (DMD), which leads to a bulky and expensive system [3-4].

Photonic integrated circuits (PICs) can offer much more compact and cost-effective solutions to generate structured illuminations. The chip-based strategy has been demonstrated by Helle [5] and Lin [6-7] for fluorescence imaging under visible and UV light. Their achievements testified that the PIC platforms can offer a new route for SIM. Considering that UV light enables higher optical resolution and auto-fluorescence of a wide variety of biological molecules [8], we are focusing here on UV PICs to generate the structured illumination. In Lin's work, the patterned illumination is shaped and sent off the chip by a pair of gratings. Using an AlO_x waveguide platform and an imaging objective lens of 0.5 NA, the maximum achieved FOV is 150 µm × 200 µm [7]. According to these results, the UV PIC-based SIM achieved an étendue G-value of 0.04, which is much lower than for the theoretical G-value (G = 1) of the collecting objective lens (FoV = 1 mm × 1 mm). The limiting factor is the size of the illumination pattern. To address this problem, we discuss here a grating design for off-chip illumination at a wavelength of 360 nm with a potential FoV of 800 µm × 200 µm. The grating out couplers defined on AlO_x waveguides are made of 5000 periods to produce a large beam. By applying a 2 nm shallow etch, an approximately uniform intensity profile of the off-chip beam is obtained with a four times FoV enhancement.

Design

For the structured illustration, one simple approach is to use a one-dimensional fringe pattern produced by a two-beam superposition and to sequentially illuminate the sample in different orientations. In our PICs, integrated grating couples the light from the waveguide to the air space as shown in Fig. 1(a). The phase matching condition that is illustrated in Fig. 1(b) fixes the diffraction angle of the illuminating beam. The projection $k_x = k\sin\theta$ of the wave vector of the free space beam diffracted with an angle θ has to be equal to the difference of the grating reciprocal vector K and of the wave number β of the guided mode, which leads to $\lambda / (n_{eff} - n_{air}\sin\theta) = \Lambda$, where λ is the laser wavelength, and n_{eff} and n_{air} are the grating effective index and cladding index, respectively. The refractive index of the aluminum oxide is 1.59 at the wavelength of 360 nm. We use the negative outcoming angle to ensure there is no unwanted higher-order diffraction. For the design of a -30° diffraction beam, the grating period should be 180 nm.

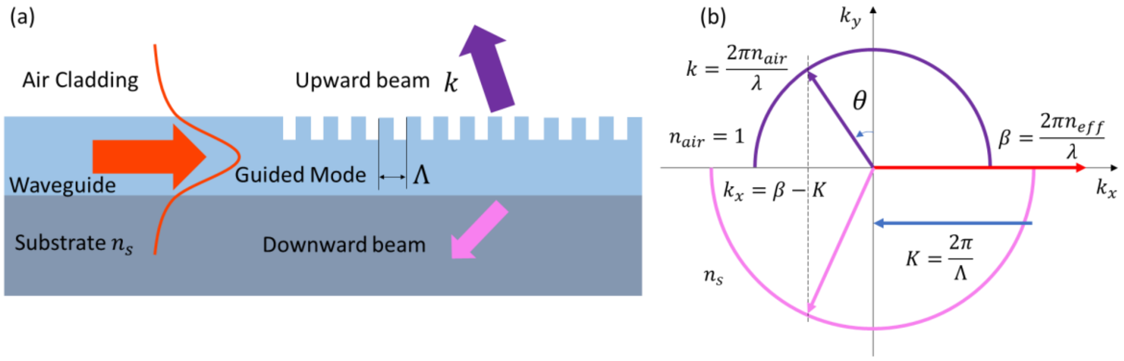

Fig. 1. (a) The illustration of the on-chip grating coupler where the single mode light is guided in the grating coupler and diffracts beam to the different directions (b) The phase match condition in the wave number space.

To obtain a larger illumination area, we set the number of grating periods as 5000 which is 5 times larger than Lin's latest design [7]. By using two such grating couplers, we can get the pattered illumination. The fringe period is defined as $\lambda / 2\sin\theta$. In our design, the theoretical fringe period will be 360 nm. The visibility of the fringe is important for reconstructing the imaging. The best visibility requires the two interfering beams to have the same intensity profile, which can be approached with long shallow etched gratings, for instance a 2 nm shallow etch grating with a 50% filling factor that corresponds to an optimized coupling efficiency.

Simulation and performance

The performance of the large grating out coupler is investigated with the Lumerical FDTD simulator. Fig. 2(a-b) illustrates the schematic of generating the off-chip fringe pattern illumination from a pair of grating couplers. By the edge coupling, the single mode 360 nm laser is guided in the waveguide. With the 1 × 2 multimodal interferometers (MMI), the mode is evenly distributed into two arms and connected to a pair of countered grating couplers. The sample is placed in the plane where the two light beams overlap. The illumination working distance D defined from the chip surface to the sample plane varies with the distance L between the two grating couplers. By using a shutter, the interference beam and the single beam can be both collected by the objective lens. Fig. 4(c-d) shows the simulated results of the single beam intensity profile and the two-beam interference fringes by setting the working distance D as 1.73 mm. In agreement with the theoretical analysis, the angle of the outcoming beam is -29.8 degrees, the fringe period is 350 nm, and the angle divergence is 0.007 degree as shown in Fig. 4d.

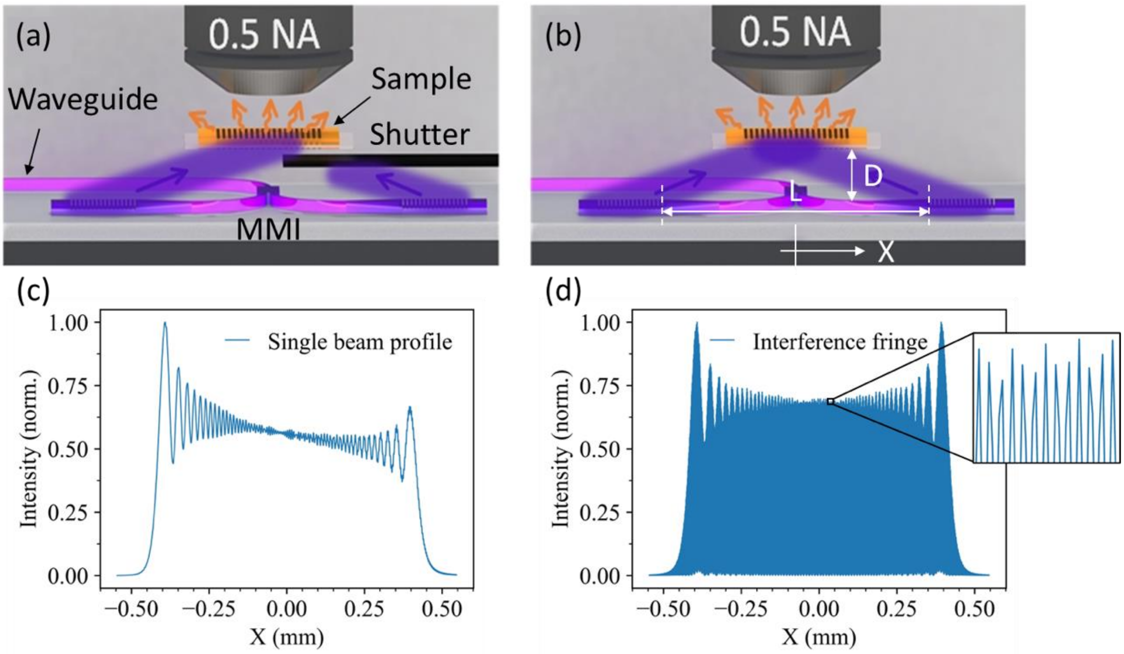

Fig. 2. (a) and (b) schematics of the single beam illumination and the two beams illumination, respectively [7]. (c) The simulated single outcoming beam profile in the degree of -30° and two beam superposition profile. (d) The simulated interference fringes with a period of 350 nm.

From the FDTD simulation, we get the desired one-dimensional fringe pattern illumination with a visibility of 0.994 ± 0.008. The intensity envelope I(x) of the fringe pattern varies with the illumination distance as shown in Fig. 3(a) for a distance D varying from 0.58 mm to 4 mm. The ideal envelope for the illumination should have a rectangular shape. However, due to the scattering at the entrance and exit interface of the grating, the homogenous region only exists in the center of the entire envelope. To determine the effective illumination region, we define the envelope deviation as $\delta = \sqrt{\sum_{-\infty}^{+\infty}\left(\mathrm{I}(\mathrm{x}) - \frac{\mathrm{I}_{\mathrm{total}}}{\mathrm{W}}\right)^2}$, where W is the targeted illumination width of an ideal rectangular profile, and the $\mathrm{I}_{\mathrm{total}}$ is the integral intensity over the entire envelope of the

FDTD profiles. By calculating the envelope deviation δ for different widths W, we find the optimal width for which δ is minimal (see the ideal rectangular envelope in Fig. 3(a)). The best illumination distance D is obtained by plotting δ for the distance D varying from 0.58 mm to 4mm in Fig. 3(b). It follows that the maximum effective illumination width with the minimal variation is 820 µm. The best plane to illuminate the sample is located at a distance D corresponding to the shortest separation of the two opposite gratings.

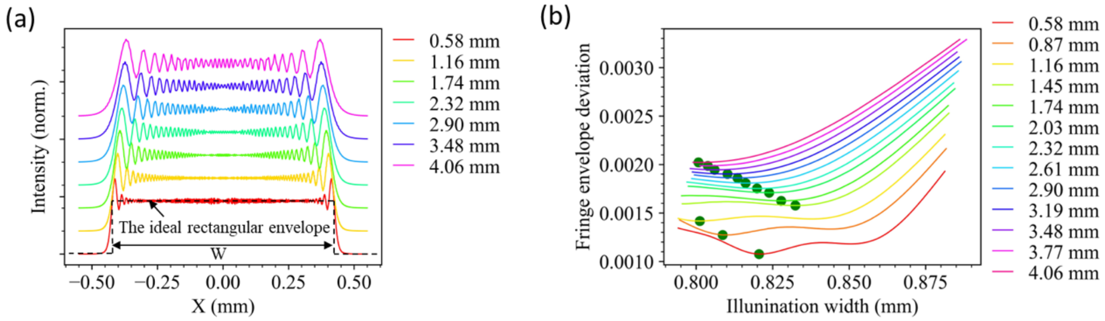

Fig. 3. (a) Intensity envelope of the far-field at illumination distance from 0.58 mm to 4 mm. The dashed line: ideal rectangular fit. (b) Deviation δ versus the width of the ideal illumination pattern for different distances. The green dots: minimal deviation δ.

Conclusion

With 5000 grating periods and a 2 nm shallow etch, an air-cladding grating coupler produces a fringe pattern illumination with an optimized uniformity at a distance D of 0.58 mm. The best illumination plane should be placed as close as possible to the chip, but the minimal distance D is limited by the length of the tapers for the current design. The transverse illumination may also be affected by the distance D. The wider the grating the longer the taper is also required in the PICs design, which will set another constraint on the best distance D. With the air cladding, the ideal 2 nm shallow etch will be challenging to fabricate considering the thickness variation of the ALO$_x$ layer is 2 to 3 nm over a 4-inch wafer. A deeper etch is possible by adding a silicon dioxide top cladding. This integrated grating optimization approach paves the way for achieving the UV PICs structured illumination microscope with high optical throughput.

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