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Design of a computer-generated waveguide hologram for integrated free space sensing

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***Abstract*—In this work we present a design of a computer-generated waveguide hologram coupler with an ultra-long working distance and wavelength multiplexing in the near infrared. An approximation method to compute the scalar field from a detour phase hologram is presented. The accuracy is comparable to FDTD but it is achieved much faster. Coupling efficiency from waveguide to free space and fabrication feasibility of design are optimized with the method.**

I. Introduction

A computer-generated hologram (CGH) has the advantage of not requiring the process of recording wavefront with a holographic plate, and it can overcome the limitation of reconstructing an image from physical reality. Over the last half century applications of CGHs have been found in display, data storage, optical security, interferometry, spectrometry and more. Most reported CGH devices rely on one or more off-plane light sources with strict requirements on their positions and angles. An exception is the computer-generated waveguide hologram (CGWH) [1,2] which can have a single optical mode confined in a waveguide layer as an input. The invention of the CGWH brings the opportunity of light source integration with the hologram, leading to more compact and easy-to-use hologram devices [3]. Extending the capability of CGWH in terms of beam focusing and multi-wavelength operation will be interesting in many sensing and metrology applications.

Here we consider a detour phase Fresnel hologram, composed of a two-dimensional array of pixels on top of a waveguiding layer. Each pixel is a small grating coupler containing one or more straight grating lines oriented perpendicular to the propagating light in the waveguide below. The grating lines have a variable offset from the pixel boundary. These offsets are used as design variables to provide the desired phase delay to the wavefront of light emitted from the grating. However, there are a few challenges to this approach: i) efficient coupling to a small focus spot in a long working distance implies an extended emission profile along a large-area hologram coupler. This requires a carefully designed coupling strength along the propagation direction; ii) the actual separations between neighboring grating lines vary with the offsets (Fig1(a)), which make it difficult to assume each pixel as an independent aperture. An FDTD simulation shows that the field computed by the Fresnel integral for the apertures is not very accurate in this case (Fig1(b)), and it results in design inaccuracies; iii) unconstrained offsets might lead to tiny design features at pixel interfaces which are infeasible to fabricate.

In this work we tackled these challenges by using both the fill factor and the offsets of the grating lines as design variables, and also taking into account the property change of each pixel due to the existence of its neighboring pixels. To guarantee fabrication feasibility we implemented a constraint on the offsets, with a price of only a small reduction in efficiency. In the end we designed a large-area CGWH for ultra-long working distance (1 cm), in which fill factor apodization is used to improve the efficiency.

II. Design Method

Without loss of generality we use a simple hologram focusing grating coupler as an example. In this case the 'image' to reconstruct is simply the focal spot of the coupler. The design space is pixelized into a 24 by 24 array, in which each pixel ($0.52 \times 0.52\ \mu m^2$) contains a single grating line. The refractive index of the waveguide is 3.2 sitting on a substrate with refractive index of 1.5. Thickness of the waveguide layer is 300 nm while the grating is etched 30 nm into the waveguide layer. The propagation constant of the waveguide mode and loss factor of the grating is calculated first from a 2D FDTD simulation (Lumerical/Ansys), and are used then to calculate phase delay and field decay from one pixel. An iterative design flow is used to optimize the offset of the grating line in each pixel, so that the total field intensity at the focal point is maximized.

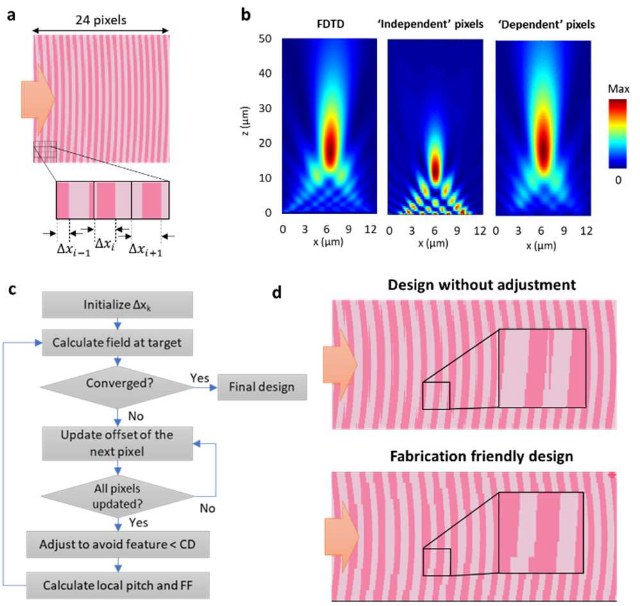

Fig.1 (a) Layout of a hologram focus grating coupler. Injected light direction marked by the orange arrow. (b) Calculated field intensity distribution in the space above the hologram by FDTD (left), Fresnel integral (middle), improved ray tracing (right). (c) Improved CGWH design flow. (d) Generated design without and with offsets adjustment. Images are enlarged in horizontal direction to show the detailed features).

Fig1(a) shows an optimized design of the hologram focus grating. The inset of Fig1(a) shows 3 neighboring pixels, where a very narrow feature appears at the interface between the first and the second pixel, and similar features appear also in other parts of the design. An FDTD simulation is performed to compare with the field computed by the Fresnel integral of 'independent' pixels, and the field computed taking into account the effect of neighboring pixels ('dependent' pixels) (Fig1(b)). In previous works on the detour phase hologram the pitch of the grating is usually assumed to be a constant (equal to the length of one pixel in this case), and so is the fill factor. However, this is an inaccurate assumption in many cases, for instance in the inset of Fig1(a) the actual distance between the grating lines in the second and the third pixel is larger than the pitch of the array by $\Delta x_{i+1} - \Delta x_i$. A large part of that field difference seen in Fig1(b) can be attributed to neglecting of local grating pitch and fill factor drifting from their default values due to the effect of neighboring pixels, which results in phase errors in the field computing. Another consequence from the assumption of 'independent' apertures is that each pixel in the hologram emits light in the same way. However, the actual emission is directional and depends on the pitch and fill factor of the grating. To improve the accuracy of field computation, the local variation of pitch and fill factor due to neighboring pixels are included in the phase calculation, and a FDTD simulation sweep is performed to find the relation between emitting directionality of a pixel and the local pitch of the grating, as well as the fill factor. The FDTD simulation needs to be done only once before the iterative optimization, so it does not add significant time to the design flow. The rightmost image in Fig1(b) shows the computed field distribution being much closer to the FDTD result after taking the mentioned effects into account. The improved design flow is illustrated in Fig1(c). Fig1(d) shows the outcome of a fabrication friendly design by introducing minor adjustments to the offsets in each iteration, compared with the non-adjusted design which contains features smaller than the critical dimension. The simulation predicts only 10% intensity drop at the target position due to this extra constraint, compared to that in the unconstrained design.

III. Large-area wavelength-multiplexing CGWH

As a proof of concept we designed a large-area CGWH for a 1-cm working distance and 3-wavelength multiplexing in the near infrared, as shown in Fig2(a). Optical inputs are from 3 single mode waveguides 1 mm away from the hologram, with a 25 µm separation between each other. Each of the waveguides sends light at a different wavelength (1300 nm, 1450 nm, 1600 nm) into the slab mode.The CGWH couples all the designed wavelengths and focusses them to a target 1 cm above it. The size of the hologram needed for this task depends on the requirement for the spot diameter at the focal plane. For a target spot diameter from 50 to 70 µm (depends on wavelength), a CGWH of $416 \times 416\ \mu m^2$ is designed with 800×925 pixels. The offsets map of the hologram is shown in Fig2(b). The running time for the program to generate this design is about 3 minutes on a laptop with Intel Core i7 @2.60GHz and 32 GB RAM.

To improve the efficiency we modulated the fill factor so that the scattering strength gradually increases in the propagation direction. However, the weakest scattering is limited by the critical dimension allowed in the fabrication. In order to increase the dynamic range of the scattering strength, the grating lines are segmented in subwavelength pitchs and the width of the segments is apodised to improve the emission uniformity along the propagation direction. The pitch of the segments is below λ_{min}/n_{eff} (0.45µm) to avoid diffraction. ig2(c) shows the calculated field intensity in xz and xy plane (z =10 mm) at 3 designed wavelengths.

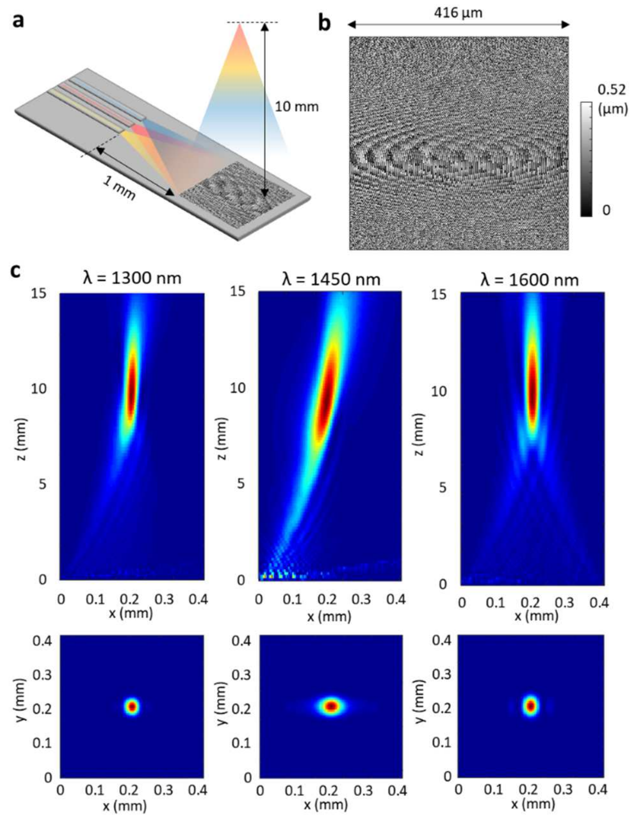

Fig.2 (a) Schematic of the CGWH photonic integrated chip. (b) Offsets map in the CGWH. (c) Calculated field intensity distribution in the space above the hologram and at the target plane (z = 10 mm) at wavelength of 1300 nm, 1450 nm and 1600 nm.

IV. Conclusion

The method presented in this work provides a fast and more accurate way to compute the fields from large-area CGWH, as compared with computationally expensive full-wave methods. The CGWH designs can be integrated with other on-chip components to enable complex interferometric measurement on targets from free space and find value in molecule/gas sensing and high throughput metrology.

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References

[1] M. Li, J. Bengtsson, M. Hagberg, A. Larsson, and T. Suhara, "Off-plane computer-generated waveguide hologram," IEEE Journal of Selected Topics in Quantum Electronics, vol. 2, no. 2, pp. 226–235, Jun. 1996.

[2] J. Backlund, J. Bengtsson, C.-F. Carlström, and A. Larsson, "Incoupling waveguide holograms for simultaneous focusing into multiple arbitrary positions," Appl. Opt., vol. 38, no. 27, p. 5738, Sep. 1999.

[3] A. G. Larsson et al., "Grating coupled surface emitters: integrated lasers, amplifiers, and beam shaping outcouplers," in Testing, Packaging, Reliability, and Applications of Semiconductor Lasers IV, Apr. 1999, vol. 3626, pp. 190–201