Engineering the Spectral Response of Waveguide Bragg Gratings Patterned By Deep Ultraviolet Nanolithography

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ABSTRACT

We demonstrate the use of deep ultraviolet (DUV) reduction photolithography, today's foremost commercial nanofabrication technology, in the patterning of integrated nanophotonic filters based on etched channel waveguide gratings. DUV photolithographic fabrication is seen to enable control over individual grating lines at the level of nanometers enabling spectral engineering of the filter function in unprecedented fashion. Novel filter apodization approaches are introduced and demonstrated that uniquely leverage DUV nanofabrication power. The demonstrated filter functions are highly relevant for coarse wavelength division multiplexing and fiber to the premise applications.

Keywords: DUV photolithography, nanophotonics, silica-on-silicon channel waveguide, etched Bragg grating, planar lightwave circuit, apodization.

1 INTRODUCTION

The structuring of electromagnetic (optical) material properties on scales substantially smaller than the wavelength of light opens up the exciting possibility to engineer, design and synthesize novel or familiar but artificially-induced behaviors and phenomena providing entirely unprecedented or substantially enhanced functionalities. The recognition of the potential that subwavelength and nanoscale engineered optical ("nanophotonic") materials, components and devices bear dates back in time several decades, yet major progress has been, until fairly recently, largely limited to theory.

Physical exploration of nanophotonic and subwavelength optical technology, while oftentimes yielding impressive results, has been impeded by complex and cumbersome fabrication methods that can lack versatility and/or precision with respect to feature size and control over placement. Examples include e-beam lithography - expensive, slow and providing very limited field sizes without stitching error -, holographic exposure, which provides access to only the most basic patterning structures, and exotic approaches such as X-ray lithography. Even nanoimprint lithography, while providing access to features sizes on the ten-nanometer scale is plagued by the latter flaw when imprint molds are derived holographically, i.e. via the interference of light fields.

The lack of a versatile and viable nanofabrication approach has been a major obstacle to the field of nanophotonics and has more often than not restricted the range of parameter space that can be effectively investigated. For the same reason, commercial exploitation of the promise and potential that nanoscale and subwavelength structures bear has been severely limited to all but their simplest renditions. Consequently, there is a need for a flexible, precise as well as commercially relevant nanofabrication approach to fully harvest the potential of optical components engineered at the nanoscale structures and to rigorously commercialize devices.

Deep ultraviolet (DUV) reduction photolithography – the powerful fabrication workhorse of the microprocessor and integrated circuit industry - provides nanopatterning capability with feature sizes of tens of nanometers and control over feature placement at the nanometer scale in a spatially coherent manner over several centimeters. The resolution of today's typical DUV stepper, deployed in volume production facilities around the globe, is 65 nm with a 25 x 33 mm^2 field. For nanophotonic component design, this enables one to address more than 10^{11} pixels on an individual basis, providing a gateway to the design of truly arbitrary patterning of optical structures at the subwavelength-level. At the same time, CMOS and related processes support throughputs exceeding one hundred wafers per hour. For ultralow-cost production, subwavelength-structured components and devices may be nano-replicated at the wafer level [1].

In the present paper, we continue to explore the use of DUV photolithography for the fabrication of integrated nanophotonic filters based on etched waveguide Bragg gratings. We had previously demonstrated that DUV photolithography makes possible the control of reflective amplitude and phase of grating elements on a truly line-by-line basis in a fully spatially coherent manner over the entire DUV field [2]. For Bragg-based filters, the ability to tailor the space-domain complex amplitude scattering function in an essentially arbitrary fashion using DUV photolithography and recently developed apodization approaches enables unprecedented freedom in terms of engineering the filter's spectral response. Design of the grating spectral transfer function via manipulation of the space-domain scattering function is guided by simple Fourier-transform relations for devices of weak to moderate reflectivity. For high reflectivity, coupled-mode analysis

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and other approaches provide accurate design methods.

One-dimensional Bragg structures have been created in fibers or channel waveguides using surface relief [2,3] or volumetric [4] diffractive surfaces and apodized in various ways [5-14]. Prior-art apodization methods previously demonstrated have not provided for very high resolution (line-by-line) control of diffractive element (grating line) amplitude and phase. Only recently has apodization leveraging DUV photolithography and thus providing control over individual grating elements been demonstrated [2]. In this previous approach the reflective amplitude of a grating element was controlled by changing its physical dimensions, specifically the element width in the direction transverse to signal propagation. It was observed, however, that the change in grating element physical dimensions simultaneously affects the effective waveguide index n_{eff} through the accompanying change of the local waveguide morphology. In turn, the index change effectively detunes the grating from it's intended resonance wavelength λ, thereby distorting the designed spectral passband.

2 DEVICE DESIGN

Figure 1a is a partial cross-sectional view of an etched silica-on-silicon channel waveguide grating illustrating the device architecture. In the grating region, the silica slab waveguide consists of a doped dual-layer core and bilateral 15-μm-thick cladding layers. The dual-layer core comprises a 500-nm thick grating layer which has a + 3 % refractive index contrast relative to the cladding and ~ 2-μm-thick upper core layer with a + 1 % refractive contrast relative to the cladding. Depicted at the interface between the two core sublayers are cross-sections of representative lithographically-patterned grating contours. The diffractive contours consist of trenches etched into the grating layer and filled with material of the upper core sublayer. The grating operates in first diffractive order with a line spacing, Λ, of about 500 nm, i.e. one half of the in-medium wavelength of resonant light. Outside the grating region the core is a single layer of the same material as the upper core with a thickness of 2.3 μm.

Figure 1b and 1c illustrate the presently investigated apodization methods. These approaches uniquely leverage the line-by-line control afforded by modern nanolithography but at the same time leave the waveguide index constant thus minimizing spectral passband distortion. In one approach (Figure 1b), each grating line is divided into two segments. Control over the element's reflective strength is obtained interferometrically by displacing the two element segments by an appropriate amount. Shifting the two segments by a distance between zero and $\lambda/(4n_{eff})$ provides continuous reflective amplitude control from 1 to 0. In an alternative approach (Figure 1c) the reflective strength of a given grating line is controlled by rotating the element about an axis located in the waveguide center. Continuous reflective amplitude control can be achieved by either method while leaving the effective index essentially constant.

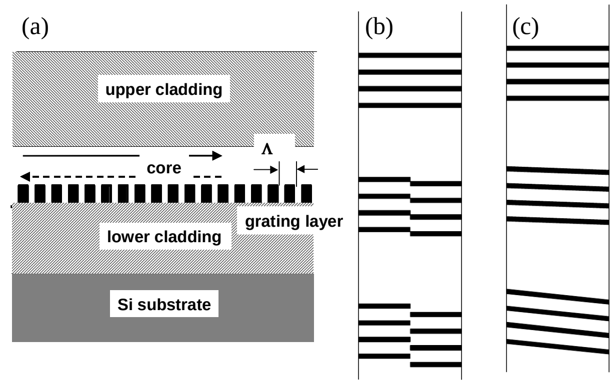

Figure 1. 1a, cross-sectional view of grating section of etched channel waveguide gratings; Λ, grating period; 1b (1c), top view of channel waveguide illustrating apodization approaches. 1b, shift-based approach; 1c, rotation-based method. Examples in both cases represent shifts yielding full, intermediate and zero reflective strength (from top to bottom).

3 FABRICATION

We have fabricated channel waveguide gratings in the silica-on-silicon platform that were apodized using the new methods. The waveguide gratings were realized in the lower subcore layer by use of a DUV optical scanner with 4× reduction ratio from a laser-written chromium-on-quartz reticle and subsequent reactive ion etching. The scanner provides the necessary resolution, of order λ/4 in the material, i.e. 250 nm, to realize the necessary grating pitch. Following the chemical vapor deposition of the upper core layer the channel waveguide was defined via i-line photolithography and etch followed by final cladding deposition.

4 RESULTS

To demonstrate the two apodization approaches of Figure 1b and 1c, two exemplary channel waveguide filters were designed to yield a flat-top spectral response with steep roll-of and side lobe suppression. Test results for TE-polarized signal are shown in Figure 2. In Figure 2a (2b) the apodization approach of Figure 1b (1c) was used. The apodization function was the same for both filters, the difference is simply the implementation method, i.e. shift- (Figure 2a) or rotation-based (Figure 2b). The gratings of Figure 2 were period-chirped to yield the ~ 15-nm passband, as is relevant to filtering applications in coarse wavelength division multiplexing (CWDM) and fiber-to-the-premise (FTTP). Passband ripple, otherwise typical of chirped gratings, was suppressed by phase and amplitude apodizing the beginning and end of each ~ 4.6 mm long grating. In both cases, excellent passband flatness and sidelobe suppression is observed. Note that the grating

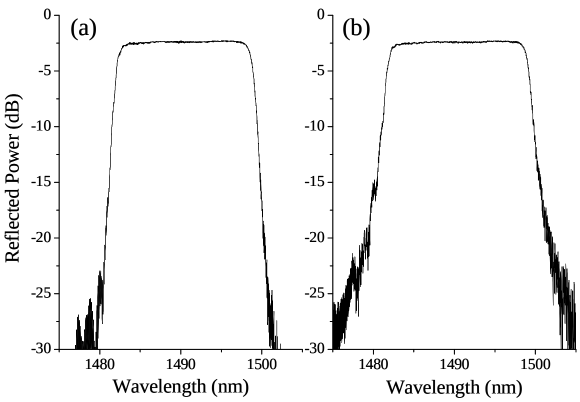

Figure 2. Measured spectral response of broadband channel waveguide gratings apodized using shift- (2a) and rotation-based approach (2b) for TE-input.

filters themselves are essentially 100% reflective, the residual insertion loss observed results predominantly from the fiber coupling.

5 CONCLUSIONS

We have demonstrated the spectral engineering of nanophotonic filters based on etched channel waveguide Bragg gratings using novel apodization approaches. The specific filter functions are relevant for implementation in CWDM and FTTP devices. More generally, our results highlight the power, flexibility and commercial viability that DUV reduction photolithography provides as today's foremost nanofabrication technology for integrated photonic devices.

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