Integrated Bragg waveguides as an efficient optical notch filter on silicon nitride platform

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Abstract. We modeled and fabricated integrated optical Bragg waveguides on a silicon nitride (Si₃N₄) platform. These waveguides would serve as efficient notch-filters with the desired characteristics. Transmission spectra of the fabricated integrated notch filters have been measured and attenuation at the desired wavelength of 1550 nm down to -43 dB was observed. Performance of the filters has been studied depending on different parameters, such as pitch, filling factor, and height of teeth of the Bragg grating.

1. Introduction

Continuous development of micro- and optoelectronics is inevitably connected with a substantial decrease of the planar structure dimensions. State-of-the-art nanotechnology allows creation of complex nanophotonic circuits with a high performance and a compact design on chip, which currently are replacing free-space optical schemes build up on the optical tables. Integrated on chip circuits have a number of advantages, such as low optical losses, no need for optical alignment, insensitivity to vibrations, small size, weight, and power consumption, but the most important is their scalability [1]. This allows development of quantum-optics integrated circuits (QPICs), which would be beneficial for quantum cryptography in the quantum key distribution systems, quantum simulations of complicated molecules, and quantum computing development increasing the data processing and computation rate gradually. One of the key prerequisites for the QPICs development is the on-chip implementation of a highly efficient single-photon source. Silicon nitride (Si₃N₄) is a promising material for nanophotonic circuits, which combine good mechanical properties, low optical absorption in the infrared (IR) and visible wavelength ranges as well as possibility for creation of single photon sources integrated into the nanophotonic circuit. One possible realization of the single-photon source is the four-wave mixing [2]. One of the main problem for such sources is an efficient pump power rejection down to -120 dB. Here, we have numerically simulated and fabricated nanophotonic waveguides with the Bragg grating of different geometrical configurations on silicon nitride platform. Such waveguides can be effectively used as notch-filters integrated into the nanophotonic circuit for the pump power suppression. For the fabricated structures, we have studied their transmission properties and the power suppression efficiency at the desired wavelength depending on the Bragg grating parameters. Data analysis demonstrates reasonable agreement between the measured and simulated characteristics.
2. Device design and fabrication

Proposed devices have a complicated structure both for the longitudinal and transverse directions, which suggests that a proper numerical simulation is required in order to obtain parameters (the width and thickness of the waveguide, the Bragg grating parameters) that would ensure the desired characteristics. We have estimated an effective refraction index of the Bragg waveguide as \( n_{\text{eff}} = 1.66 \).

The grating is defined by a few parameters: pitch of the Bragg grating, \( \Lambda = \lambda/(2\times n_{\text{eff}}) \), filling factor, \( ff = a/\Lambda \), height of teeth, \( h \), with \( a \) being the width of a tooth (Figure 1(c)). By choosing proper parameters, one could efficiently suppress a spectral component in the transmitted spectra, or even tune up the reflectivity for that component [3]. With increase of \( \Lambda \) or \( ff \), wavelength of the spectral component is also increased, and increase of \( h \) affects the efficiency and controls the width of the notch. According to the numerical simulation, a telecommunication-wavelength (1550 nm) notch filter should have Bragg’s grating pitch of 466 nm, filling factor \(-0.5\) and the waveguide width \( W = 1 \mu m \).

Basing on the provided above relations, we have developed and fabricated a nanophotonic structure, which included a pair of focusing grating couplers (FGCs) and the Bragg grating in between them, as shown in Figure 1.

![Figure 1](image1.png)

**Figure 1 (a, b, c, d).** (a) Optical photograph of a fabricated structure; (b) SEM image of the FGC; (c) Zoom-in in the Bragg grating (SEM) (\( \Lambda \) – pitch, \( W \) – width of the waveguide, \( h \) – height of the teeth, \( a \) – width of a tooth); (d) Zoom-in in the FGC (SEM).

On the horizontal parts of the structure, the Bragg grating was formed, as depicted in Figure 1(c). Also shown the waveguide and Bragg grating parameters. Coupling of the incident power to the waveguide structure was done with use of a FGC depicted in Figure 1(b) and shown in greater details in Figure 1(d). For the devices, multi-layered substrates were used, with thicknesses of silicon (Si), silicon oxide (SiO\(_2\)), and silicon nitride (Si\(_3\)N\(_4\)) of 450 µm, 2.6 µm, and 450 nm, respectively. The rib waveguide was formed from Si\(_3\)N\(_4\) layer by means of e-beam lithography with use of a positive resist ZEP 520A providing good contrast during the lithography. NanoMaker software [4] was used for proximity effect correction and precise adjustment of the e-beam exposure time. Removing of the exposed material was done by reactive-ion-etching (RIE) in CHF\(_3\)-Ar mixture. The resist residuals
were cleaned out with help of the oxygen plasma. In order to evaluate performance of the notch-filter depending on the Bragg structure parameters, we have intentionally varied the Bragg grating pitch, filling factor, and height of the teeth during fabrication of the devices.

3. Experimental setup and results
In order to characterize the devices, we have experimentally analyzed their transmission at room temperature, and precisely measured attenuation at the desired wavelength (around the telecommunication wavelength, $\lambda = 1.55 \, \mu m$). Experimental setup incorporated wide-band sources of light, whose power were fed to the device through a polarization controller and a fiber array which includes a set of SM-28e fibers fixed with a precise spacing of 250 $\mu m$ and tilted by 8° to the device is shown in Figure 2(a). The device itself was mounted on to a table equipped with micrometer-step 3D positioner needed for the device – to – fiber array alignment.

![Figure 2 (a, b). (a) Experimental setup diagram; (b) Transmission spectrum of a device with $\Lambda = 466 \, \text{nm}$, $ff = 0.5$, $h = 100 \, \text{nm}$, demonstrating desired attenuation at wavelength of $\sim 1.55 \, \mu m$. 25 dB attenuation as well as the power decreasing at higher and lower wavelengths is due to introduced by the two FGC in the nanophotonic circuit.](image_url)

Coupling to the device was realized through the FGCs, one of them was used to irradiate the device, and the other one – to measure the power transmitted through the Bragg grating. Transmitted power was analyzed by an optical spectrum analyzer (OSA) controlled by a PC. A measured curve is depicted in Figure 2(b). Experimentally evaluated dependence of the notch wavelength on the grating pitch is represented in Figure 3(b): with increase of the pitch the notch-wavelength is also increased.

The same effect is observed by increasing the filling factor which is in line with the simulations and allows one to fabricate a notch-filter at a desired wavelength. Dependence of the transmitted power versus the grating periodicity is given in Figure 3(c) showing increase of the notch-filter efficiency from -5 dB to -43 dB with increase of the grating periodicity from 150 to 2350 at the wavelength of 1.55 $\mu m$ and the other Bragg’s grating parameters fixed ($\Lambda = 466 \, \text{nm}$, $ff = 0.5$, $h = 100 \, \text{nm}$). Grating periodicity of 2350 takes a length of $\sim 1 \, \text{mm}$. With linear approximation, we are able to produce notch-filters with the desired attenuation at the selected wavelength. Also, changing the teeth height one is able also to tune the notch-filter efficiency and its width as shown in Figure 3(a).
With decrease of the teeth height, the FWHM is also decreased. The data were obtained for devices with fixed Bragg’s grating pitch and filling factor ($\Lambda = 466$ nm, $ff = 0.5$). FWHM is decreasing from 43 nm at $h = 500$ nm down to 1.5 nm at $h = 50$ nm. This result ensures development of notch-filters with desired selectivity.

4. Conclusion

To conclude, we have shown that Bragg’s waveguides made from silicon nitride could be efficiently used as filters operated in complex quantum-optics integrated circuits, such as for filtering out pumping power driving single-photon sources. By varying the Bragg grating pitch, filling factor and the height of the teeth, a notch-filter can be designed and fabricated with the desired characteristics, such as notchwavelength, spectral selectivity (i.e., FWHM of the notch-line), and efficiency. By extrapolation, one may predict that a 3.2-mm long Bragg’s waveguide would be needed for unwanted power suppression down to -120 dB. Further work will be devoted to maturing of the technological steps, which is crucial for technological repeatability and improvement of the spectral properties of the devices. As a next step, on-chip integration of the filter with a multi-element circuit including a single-photon source based on four-wave mixing should be considered.

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