Optimization of contra-directional coupler based on silicon nitride Bragg rib waveguide

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Abstract. We report on the development and fabrication of a contra-directional coupler based on the Bragg waveguide on Si$_3$N$_4$ platform. Transmitted and reflected by the contra-directional coupler spectra were measured. The reflected spectra exactly matches the one notched by the main channel of the coupler. Losses are about 3dB, coupling to the directing branch of the coupler is practically lossless. FWHM of the transmitted (reflected) spectra is 3.46 nm.

1. Introduction
Quantum photonic integrated circuits (QPICs) enables the implementation of complex architectures on a single chip [1] allowing to overcome the high losses and large footprint of free-space optical systems. The research interest is growing towards the integration of single-photon sources, single-photon detectors and passive elements, such as filters, splitters and resonant cavities. The development of low-loss passive components capable of spectrally select and distribute the optical modes propagating into a photonic waveguide would enable efficient filtering of pump light in case of optically excited single photon sources and for multi-channel (i.e. parallel) processing of quantum information.

Bragg’s grating has been proposed as key-element for a large range of applications, such as: lasers [2], wavelength-division multiplexing (WDM) filters [3] and optical sensors [4]. Here we present the realization of nanophotonic contra-directional coupler (CDC) based on the Bragg waveguide [5] capable of spectrally split the propagating signal with low insertion losses.

2. Device design and fabrication
For the devices fabrication a multi-layered substrate, 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, has been used. The rib waveguide has been realized in the Si$_3$N$_4$ layer. Si$_3$N$_4$ was chosen because it has low absorption in the visible and IR wavelengths, a high refractive index ($n \approx 2$) and also demonstrates good mechanical properties.

With use of the COMSOL Multiphysics, numerical simulation of the Bragg waveguide properties has been carried out, including the analysis of the electric field intensity distribution along the waveguide CDC for both TE$_1$ and TE$_2$ modes (Figure 1(b)). Effective mode indices ($n_1$ and $n_2$) and the reflection wavelength have been evaluated using the phase-matching condition [6] (Figure 1(a)):

$$\lambda_C = 2\Delta n_{av} = \lambda(n_1 + n_2)$$  \hspace{1cm} (1)
where $\lambda$ is the central wavelength of the reflected spectrum, $A$ is the Bragg grating period, and $n_1$, $n_2$, $n_{av}$ are the effective refractive index and average refractive index, respectively. For the simulation, the width of the waveguide ($W_{in}$, $W_{out}$) and their separation $G$ have been varied. The structure has been optimized for operation in the telecommunication wavelength range, around 1550 nm. Calculation of the parameters of the Bragg grating, such as the Bragg grating period ($A$), filling factor ($ff = a/A$), height of teeth ($h$), and study of the waveguide structure transmittance depending on these parameters, are given elsewhere [7].

![Figure 1 (a, b).](image)

**Figure 1 (a, b).** (a) Calculated effective mode indices with the condition of phase matching and certain reflected wavelengths; (b) The calculated intensity distribution of the electric field along the CDC waveguides for the first (TE1) and second (TE2) modes.

The CDC consists of two adjacent anti-phase Bragg waveguides [5] One of these waveguides, referred to as the main waveguide ($W_{in}$), serves as a carrier, supporting propagation of the signal in a wide spectral range, while the other waveguide ($W_{out}$) is used for directing the notched part of the spectrum, which is reflected back and propagates in the backward direction relative to the original direction of the wave (Figure 2(b)). Focusing grating couplers (FGC) have been used for the single mode fiber – to – waveguide and waveguide – to – single mode fiber coupling of light (Figure 2(c, d)). The main waveguide has an input and output couplers allowing for the transmission spectrum control. The coupled waveguide is equipped with the output coupler only allowing for the reflected wavelength measurement and control. The integrated device had three optical ports (an input, an output with a transmitted signal, and an output with a reflected signal) and two unconnected Bragg waveguides (Figure 2(a)).
Figure 2 (a-d). (a) Optical micrograph of a fabricated device; (b) SEM image of CDC section based on the Bragg waveguide ($A$ is a period of the Bragg waveguide, $W_{in}$ is a width of the main waveguide, $W_{out}$ is a width of the branch with reflected signal, $h$ is a height of the teeth, $a$ is a width of a tooth, $G$ is a spacing between the teeth of the two waveguides); (c) SEM image of the FGC; (d) Zoom-in of the FGC (SEM).

The structures were fabricated by means of electron-beam lithography using a positive resist ZEP 520A, providing good contrast during the lithography. NanoMaker software [8] 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.

3. Experimental setup and obtained data

In order to characterize properties of the fabricated devices, transmitted and reflected spectra were measured (Figure 3(b)). A piezo-actuated positioning system has been used to optimize the alignment between the FGC and the fiber array thus maximizing the transmitted signal. A tunable narrow line wide-band laser was used as a light source which was carried through a polarization controller and then delivered to the device using one channel of fiber array (FA) placed above on-chip focusing grating coupler (FGC) [9] (Figure 3(a)). The grating couplers are located at a distance of 250 $\mu$m from each other, the same distance is given between the individual optical fibers in the array. A wide spectrum of radiation from a tunable laser is supplied into the main waveguide of the structure through an input coupler. Spreading along the Bragg waveguide, the narrow spectral range determined by the parameters of the Bragg grating ($A$, $f$, $h$), is reflected back and passes into the diverging waveguide. As a result, a transmission spectrum is eliminated from the coupler output, and the reflection spectrum is measured at the diverging coupler output (Figure 3(b)). As was found, the reflected spectra coincide with the notched spectra in the main waveguide. A PC was used to control the laser and power detector which was used to measure the transmitted and reflected power.
Device insertion losses, extracted via transmission normalization of on-chip reference circuit with two FGCs and waveguide between them, were about -3 dB. As depicted in Figure 2(b), FWHM of the transmitted (reflected) spectra is 3.46 nm. Coupling to the diverging branch of the coupler is practically lossless. By optimizing the width of the coupled waveguide ($W_{\text{in}}$) and the spacing between the waveguides ($G$) aiming at the maximization of the reflected power into the coupled waveguide.

We estimated the difference between the normalized values of the maximum reflected power ($R_{\text{max}}$) and the minimum transmission power ($T_{\text{min}}$) for the reflected spectral component ($\Delta RT = R_{\text{max}} - T_{\text{min}}$) (Figure 3(c)). We found as optimal parameters for the structure: $W_{\text{in}} = 1 \mu$m, $W_{\text{out}} = 1.5 \mu$m, $G = 50$ nm, corresponding to the maximum transition of the reflected spectral component from the main to the outgoing waveguide.

In the colorplot if Figure 3(c) is reported the transmitted signal at different $W_{\text{out}}$ width and gap. The red region indicates the maximum transmission region, while the green and blue areas correspond to increasingly lossy regions.

By varying the Bragg grating period at a fixed filling factor $f f = 0.5$ and teeth height $h = 100$ nm, we have measured dependence of the notched wavelength on the period (Figure 2(d)).

### 4. Conclusion

It was demonstrated that optimized contra-directional coupler based on the Si$_3$N$_4$ waveguide can be successfully used for notching aspecified wavelength range and directing it into another waveguide with very low losses. Further work will be devoted to the improvement of the spectral characteristics.
of the contra-directional coupler, development of the multi-channel demultiplexer as well as its integration with the waveguide integrated superconducting nanowire single-photon detectors (WSSPDs) on silicon nitride platform [10].

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