CWDM demultiplexer using anti-reflection, contra-directional couplers based on silicon nitride rib waveguide

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Abstract. We report on the development and fabrication of a 9-channel coarse wavelength-division multiplexing for telecommunication wavelengths (1550 nm) using anti-reflection contra-directional couplers, based on silicon nitride (Si₃N₄) rib waveguide. The transmitted and reflected spectrum in each channel of the demultiplexer were measured. The average full width at half maximum of the transmitted (reflected) spectra is about 3 nm.

1 Introduction

Today, coarse wavelength-division multiplexing (CWDM) and dense wavelength-division multiplexing (DWDM) data transmission technologies are the basis for most fiber-optic communication lines [1]. Due to the active development of quantum photonic integrated circuits (QPICs), implementation of CWDM systems on a single chip represent a promising solution to obtain low-loss and compact building blocks which can be replicated on large scale. In this work we report on the development and fabrication of a 9-channel CWDM demultiplexer for telecommunication wavelengths using anti-reflection (AR), contra-directional couplers (CDCs) based on corrugated rib waveguide structure. The rib waveguide has been realized on silicon nitride platform, which combines low absorption at visible and IR wavelengths, a high refractive index (n ≈ 2), good mechanical properties as well as CMOS compatible fabrication technology.

2 Device design and fabrication

The developed structure consists of a long curved comb waveguide with a periodic anti-phase Bragg grating (Fig. 1(a)). This waveguide is the main transmission line or the main channel in which the light propagates. The grating is not located along the entire length of the waveguide, but only in chosen areas. Along each of the sections, another comb waveguide with an anti-phase Bragg grating is located very closely. These waveguides do not intersect with the main channel and are the demultiplexer “escape” channels to which filtered (based on its wavelength) light is diverted. Together, both waveguides constitute a single CDC [2-3]. The grating periods (Δ) of both waveguides coincide in one channel, but vary for different channels. The designed and fabricated structure has 9 channels (sections). The period...
Figure 1 (a, b). (a) Schematic image of a fabricated 9-channel CWDM demultiplexer. (b) SEM image of CDC section based on the Bragg waveguide ($\Delta$ 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).

... increases by 0.625 nm. The length of each section is 1000 periods (Fig. 1(b)). Also on each outgoing channel there is a filtered output to the optical fiber with the help of a focusing grating coupler (FGC) [4] and a long section of the waveguide for the subsequent fabrication of superconducting single-photon detectors on the waveguide (WSSPDs) [5].

The range to be filtered out is determined by the parameters of the Bragg grating as

$$\lambda_c = \Delta \times 2n_{eff,av},$$

where $\lambda_c$ is the central wavelength of the reflected spectrum, $\Delta$ is the Bragg grating period, $n_{eff,av}$ is the average refractive index, respectively [2].

The structures were fabricated by means of electron-beam lithography using a positive resist ZEP 520A, providing good contrast during the lithography. NanoMaker software [6] 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 the fabricated structure, the total transmittance of the main channel of the demultiplexer and the reflection in each output channel were measured. Light from a tunable laser source through a polarization controller was brought into the structure using an optical fiber array, one of the outputs of which was located in front of the input focusing grating coupler (FGC) [4] structure, the other output of the array was coupled to the output FGC, which made it possible to measure the total transmittance of the structure. The other outputs of the optical fiber array were located above the output channel of the demultiplexer output channels; with the help of them the reflected light was recorded for each channel. In the measured transmission spectrum there is a signal corresponding to all of the 9 channels (Fig.2 (a-b)). The average FWHM of the output channel spectra is about 3 nm.
Figure 2 (a, b). (a) Schematic view of the experimental setup including: tunable laser source, multichannel photonic chip, low noise photodetector and PC. (b) Normalized transmitted and reflected spectra of the fabricated 9-channel CWDM demultiplexer.

4 Discussion

We observe that, in addition to the peak at the central wavelength ($\lambda_c$) of the spectrum of each channel, additional side-peaks at wavelengths ($\lambda_{r1}$ and $\lambda_{r2}$) are present (Fig.3(a)). The presence of pronounced additional peaks results from a different behavior of the CDC demultiplexer on respect to the one observed from previously fabricated single CDC structures [3].

To explain this effect, we assume that the additional peaks at side wavelengths are associated with the non-uniformity of Bragg grating fabrication on the inner and outer faces CDC, that was due to the peculiarities of the technological processes. To confirm this assumption with the help of SEM image, we measured in detail the dimension of the Bragg grating teeth and carried out a numerical simulation of the effective refractive index $n_{eff}$. Figure 3b shows the result of simulation the effective refractive index for two different cases when the optical radiation power passes through a wider waveguide (TE$_1$, $n_{eff_1}$) and a less wide waveguide (TE$_2$, $n_{eff_2}$) [3].

In the general case, when the teeth outside the CDC are equal to the teeth inside, but shifted by half a period, a completely destructive interference of light reflected from different parts of the waveguide teeth occurs and no additional peaks are observed [2]. In our case the shift difference remains, but the teeth sizes on both sides of the waveguide do not match, only partial destructive interference of the reflected light occurs and additional peaks are seen corresponding to each effective refractive index in each waveguide ($n_{eff_1}$ and $n_{eff_2}$) of the CDC. It was determined that additional peaks $\lambda_{r1}$ and $\lambda_{r2}$ at side wavelengths match $n_{eff_1}$ and $n_{eff_2}$ calculated for TE$_1$ and TE$_2$ modes, and $\lambda_c$ match $n_{eff_{av}}$ average effective refractive index.

Experimental and simulations results are in good agreement with the literature [2]), and further improvement of the demultiplexer is associated with both the improvement of the fabrication technology and the integration of superconducting single-photon detectors on a chip [5]).
Figure 3 (a, b). (a) Normalized transmitted of a first channel CWDM demultiplexer. The main peak of the reflection in the channel ($\lambda_c$), an additional peaks in the channel ($\lambda_{r1}$ and $\lambda_{r2}$). (b) Simulated effective refractive index of a first channel CWDM demultiplexer (the main peak of the reflection in the channel ($\lambda_c$) corresponds to $n_{av}$).

5 Conclusion
We fabricated a 9-channel CWDM demultiplexer for telecommunication wavelengths with a bandwidth of about 3 nm. We also report on the investigation of an additional peak in the transmission spectrum of each channel. To explain additional peaks at side wavelengths, a numerical simulation of the effective refractive index of the fabricated CDC was carried out. Further work will be directed to fabrication based on the fabricated waveguides of superconducting single-photon detectors fully integrated with the demultiplexer (WSSPD) [5].

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