Design of a Broadband Integrated Notch Filter in Silicon Nitride

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***Abstract*—A broadband integrated notch filter, using the silicon nitride (Si_3N_4) platform, is presented. It achieves an extinction ratio (ER) of 60 dB and a full width at half maximum (FWHM) of 10 nm at the central wavelength (CW) 785 nm. The main filter components are Bragg gratings (BGs). For separating the occurring reflections from the input waveguide, two identical BGs are combined with a directional coupler (DC) acting as optical circulator. The 3-dB bandwidth of the passband (790 nm to 1200 nm) is more than 400 nm.**

I. Introduction

Optical filters represent a key component in photonic integrated circuits, e.g. for separation of channels in wavelength division multiplex (WDM) receivers or in sensor applications. In this work the focus is on a notch filter characteristic that is required e.g. for the suppression of pump signals in Raman spectroscopy. A common filter architecture is based on ring resonators [1]. They are compact and achieve high ERs. However, they support closely-spaced resonant modes and consequently their free spectral range is strongly limited [2]. In this regard, contra-directional couplers are more suitable devices [2]. The challenges lie in their complex design and in achieving a large ER. Another filter structure are BGs that can enable an unlimited free spectral range characteristic for a specific wavelength range [3]. In addition, their ER and FWHM can be tailored by different geometric structures. Problems may arise, because the reflected signal parts could affect the system in an undesired manner like destabilizing the pump laser. Therefore, an integrated optical circulator is needed for separating reflected from incident signals. One approach is based on a Mach-Zehnder interferometer (MZI) configuration [3, 4]. This working principle will be discussed in the following section.

The main field of application of the presented system is on-chip Raman spectroscopy. The implemented filter rejects signals at the CW of 785 nm and shows an efficient transmission of longer wavelengths. The choice of this CW is explained by the fact, that an excitation with such a wavelength leads to a good balance between Raman scattering efficiencies and the occurrence of undesired fluorescence [5]. As result of the scattering processes, new wavelengths are induced, which carry information about molecular properties of investigated substances. Therefore, a filter is required, whose transfer function doesn't show a significant attenuation till at least 1150 nm. That value corresponds to a Raman shift of 4000 cm^{-1}, which sets an upper limit for common organic Raman measurements [6]. Furthermore, the intensity of the pump signal is several orders of magnitude higher than the induced Raman signals. To avoid cross talk at the detection, the filter should enable a specified ER around 60 dB. Both demands are challenging.

The optical simulation environment is based on the eigenmode expansion method (EME) and the rigorous coupled mode theory (RCMT) using the FIMMWAVE and FIMMPROP software from Photon Design [7, 8].

II. Design of the Filter

An already known principle of the filter ([3, 4]) is shown in Fig. 1(a). The pump signal at port 1 propagates in a monomodal waveguide for 785 nm (height: 250 nm, width: 470 nm). A DC splits the signal equally between the outgoing arms. The two BGs are identical and act as an optical mirror for the green marked signal parts at the CW. The reflections pass the first 3-dB coupler again. Taking the added phase shift into account, there is destructive interference in port 1 and constructive interference in port 2. Thus, the notch filter is realized by separating the forward propagating wavelength from the reflected part. Due to the wavelength selectivity of the BGs, signals of longer wavelengths (orange, red) are transmitted undamped. The equally split parts are combined again by another 3-dB coupler at the output, as depicted in Fig. 1(a). As this is in general a MZI configuration with additional BGs, the notch filter characteristic is superposed by a MZI characteristic. This works well, if the used DCs show a nearly continuous 3-dB characteristic, like for the orange signal. However, the design of a DC with flat coupling ratio over a large wavelength range is challenging.

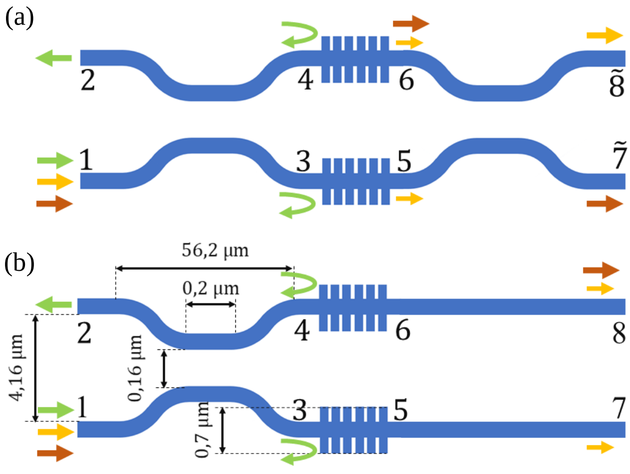

Fig. 1. In (a) a common setup of the filter system is shown. A 3-dB coupler realized by a DC splits the incident signal equally among the outgoing arms. Each BG in the corresponding arm reflects the green marked signals, which fulfill the Bragg conditions. The reflections pass the first 3-dB coupler again and interfere constructively at port 2 and destructively at port 1. Signal parts with longer wavelengths (orange and red) pass the BGs nearly undamped and are combined again by another 3-dB coupler. In (b) a proposed setup with improved frequency characteristic in the passband is presented.

In Fig. 2(a) the transfer function of a designed conventional DC in Si_3N_4 is shown. For longer wavelengths, the coupling coefficient increases. At around 960 nm a total coupling into the crossed waveguide takes place. For a further increase of the wavelength, the power couples back to the origin output waveguide, i.e. the coupling ratio is not constant. Fig. 2(b) shows the simulated transmission characteristic of the MZI, constructed as depicted in Fig. 1(a) omitting the BGs. The 3-dB bandwidth of the passband is less than 100 nm, due to the occurring resonance at 960 nm.

The main filter components are the BGs. Their design is kept simple. By changing the width of the waveguide periodically by a factor of 1.5, fulfilling the Bragg condition for 785 nm, and using at least 430 periods the required ER of 60 dB and FWHM of 10 nm are reached. The corresponding reflection and transmission curves are shown in Fig. 2(c).

In this work an alternative setup for the notch filter is proposed, as depicted in Fig. 1(b). Omitting the combiner at the output, no wavelength range limitation due to the MZI configuration occurs for the transmitted signal parts. Therefore, the forward transmission maps the coupler characteristic, whereas the reflections map the MZI characteristic.

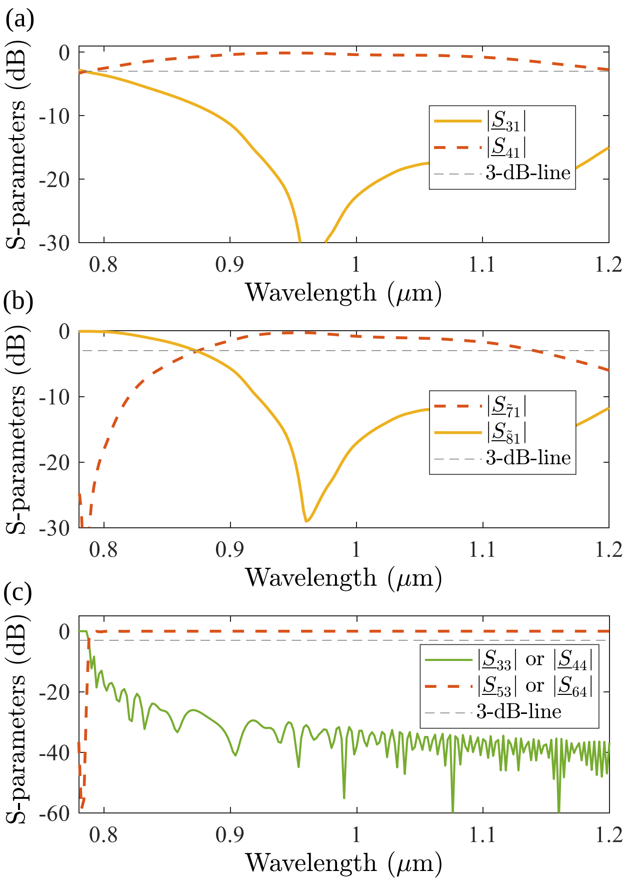

Fig. 2. Simulation results for single components of the filter. In (a) the scattering parameters (S-parameters) of the designed DC are shown. For the considered range of wavelength, the power couples mainly to the crossed waveguide. The transmissions to the output ports $\tilde{7}$ and $\tilde{8}$ of a MZI, build up as depicted in Fig. 1(a) omitting the BGs, results to (b). Due to the deviation of the 3-dB characteristic of the DCs for longer wavelengths, the signals leaving port $\tilde{8}$ show a transmission over 3 dB up to 870 nm only. The reflection and transmission of a designed BG are shown in (c). At the CW at 785 nm an ER of 60 dB and a FWHM around 10 nm are achieved.

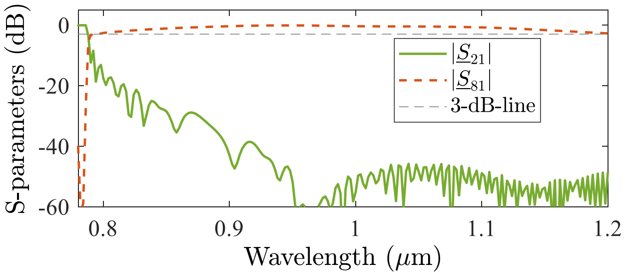

Fig. 3. The S-parameters of the presented system from Fig. 1(b) are illustrated. An ER of 60 dB can be realized. Signals with wavelengths between 790 nm and 1200 nm transmit with lower attenuation than 3 dB to port 8. This results in a 3-dB bandwidth of more than 400 nm. The reflected signal can be coupled out from port 2.

Fig. 3 visualizes the resulting transfer functions. For this architecture the demand of an ER around 60 dB is reached, whereas the passband (790 nm to 1200 nm) has a 3-dB bandwidth of more than 400 nm. To the best of our knowledge, there's only one previous work dealing with this scope [9]. In contrast to that, the filter implemented in this work has a simpler structure and requires less chip area.

III. Conclusion and Outlook

Systems for on-chip sensorics, especially on-chip Raman spectroscopy, require ultrabroadband integrated filters. Design considerations and simulation results of a notch filter for this application are presented. The filter shows an ER of 60 dB and a FWHM of 10 nm for a CW at 785 nm. The attenuation of signals between 790 nm and 1200 nm is less than 3 dB. So, the 3-dB bandwidth is over 400 nm. In addition, by adapting the coupler and the BGs, an adequate filter for fluorescence spectroscopy can be generated. The add/drop characteristic makes the filter also interesting for other domains of applications like WDM channel separation.

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