Peculiarity of multi-reflector filtering technology

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Abstract: *Paper described recent results of numerical investigation by FDTD method of novel widely tunable TO and AO filters and reconfigurable optical add/drop multiplexers (ROADMs) employing multi-reflector beam expanders. A novel design of thin SOI ROADM structures that utilizes 2D-grating, nano-grooves, and double waveguides with* p^+*-doping regions to provide single mode behavior and better manufacturability is presented.*

Introduction

Reconfigurable optical add/drop multiplexers (ROADMs) are among the most demanded devices that can increase flexibility and capacity of wavelength-division-multiplexing (WDM) fiber optic networks. A great number of different technologies and device structures for ROADMs implementation has been already developed [1]. Although a great progress has been achieved in recent years, none of actual technologies could be regarded as ideal to substitute all the others in the near future.

The large part of current research activity is focused on further improvement of existing technologies as well as on the development of new emerging technologies, in order to develop better optical devices for WDM.

In order to reduce the cost per channel needed for the commercialization of WDM systems, tunable optical filters (TOFs) and ROADMs based on integrated optics and patented multi-reflector (MR) filtering technology have been already proposed [2-7]. This technology combines physical phenomena of wave-guiding, reflection and constructive interference in a novel way. The MR filtering technology accomplishes filtering operation by spatially expanding the optical beam through a patented MR-beam expander (BE) [8], then tuning and filtering the desired wavelength by an acousto-optic (AO) Bragg sell (see **Fig. 1**.) or by a set of tunable channel waveguides (see **Fig. 2**) and by constructive interference of multiple sub-beams, combined at the output channel waveguide by another beam expander. Multi-reflector technology provides the possibility of developing tunable devices (TOF and ROADM) on different materials (silicon, polymer, lithium niobate) [2-5], allowing partial reflector manufacturing, optical phase tunability and low optical losses in the single-mode waveguides. Nowadays, MR-filtering technology has not yet been studied experimentally and its theoretical study is not completed, containing a lot of unresolved aspects.

This paper described general peculiarity of milti-reflector filtering technology that is accompanied by a number of numerical simulations performed by finite difference time domain (FDTD) method in order to demonstrate the device proof-of-concept.

I. Multi-reflection technology in $LiNbO_3$

The origin of multi-reflector filtering technology comes from the research devoted to developing compact acousto-optic tunable filters (AOTF) with improved spectral resolution. This aim accomplished by implementing highly dispersive multi-reflector beam expanders (MR-BEs) (see **Fig. 1**) that evolve the fruitful conception of holographic grating beam expander. An MR-BE consists of a channel optical waveguide of chalcogenide As_2S_3 glass (on $LiNbO_3$ substrate) that is crossed by periodically spaced partial reflector strips.

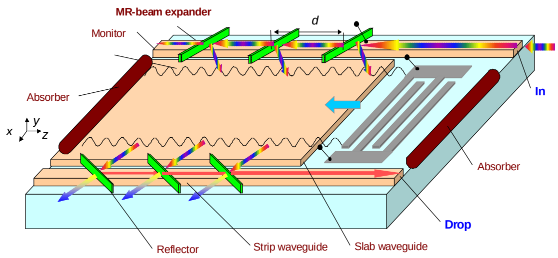


Fig.1: Noncollinear AOTF with MR beam expanders.

Quantitative description of MR-AOTF is very complicated and can be studied only numerically. Here we present the first simulation of device by FDTD method. To fasten simulations 3D structure has been replaced by 2D analogy using the effective index method (EIM) that decomposes 3D strip waveguide into two 2D slab waveguides. By this approach, we examine MR-AOTF by means of 2D FDTD method by software tool FullWAVE from RSoft Design Group, Inc. [9]. Practically, this 2D situation corresponds to the 3D-waveguide structure with reflectors whose area overlaps guided mode in transverse direction (Y).

Typical results of MR-AOTF simulation by the FDTD method is presented in **Fig. 3**. Effect of phase grating induced by SAW is examined by static grating of refractive index with period around L = 1.2 µm, and aperture L = 50 µm. The beam expander splits input optical beam into 32 sub-beams that interact with SAW. Note, that diffraction efficiency of expanded multi-beam light is equal to that of single optical beam with the same total aperture (150 μm). Diffracted beam enters the second beam expander and at particular optical wavelength it is effectively dropped and forwarded to the end of device. By changing the SAW wavelength (1.1μm<L<1.4 μm) one can change also filtered optical wavelength (see **Fig. 3**) within the large tunable range 98 nm to work with C- or L- bands.

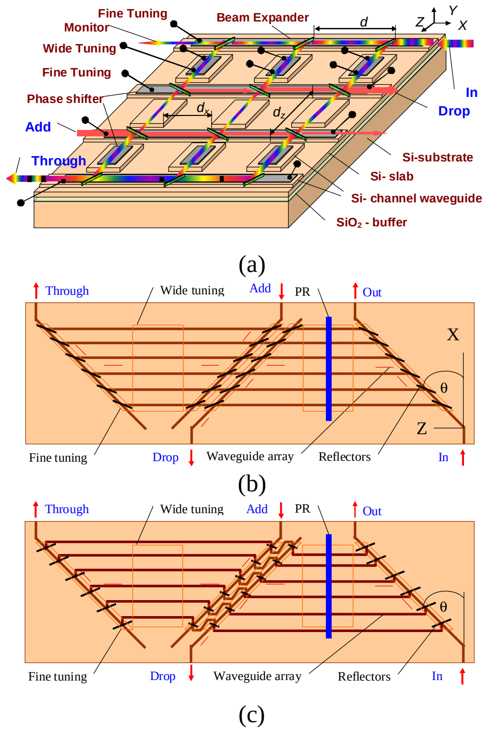


Fig. 2: General view of thermo-optic MR-ROADM with (a) rectangular; (b) slanted arrangement with large incident angle; (c) slanted arrangement with small incident angle.

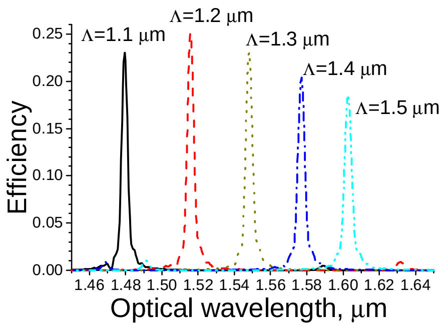


Fig. 3: The response of MR-tunable filter at different SAW wavelengths. FWHM = 4.5 nm.

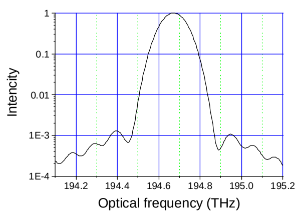


Fig. 4: Simulated response of MR-AOTF. SAW frequency 1227 MHz, aperture 0.58 cm, internal loss IL_D= -3.6 dB.

Current *3dB* linewidth (FWHM=*4.5* nm) is a result of small device dimensions *(150´70 mm^2)* that can be analysed by FDTD due to limited memory and capacity of our computer. Our independent simulations taking into account spectrum approach [4] show that by some increase of device area (within 1 cm^2) and by optimum choose of variable reflection coefficients of beam expander reflectors one can develop set of AO devices working with 25 GHz or smaller ITU grid (see **Fig. 4**).

II. Multi-reflection technology in SOI

The general view of MR-ROADM based on Silicon-on-Insulator (SOI) rib waveguides and thermo-optic phase shifters is shown in **Fig. 2**. Typical MR-ROADMs [3, 5] contain four multi-reflector beam expanders [8], constituted by the optical waveguide array crossed by periodically spaced partial reflector strips. SOI partial reflectors can be fabricated by etching a deep groove and filling it by a material with different optical properties. The technology of deep etching and filling is widely used for MEMS and Bragg reflectors.

The operation of thermo-optic MR-ROADM has a lot of common features with the AO counterpart. Optical signal that comes to the Drop and Through outputs strongly depend on the phase delay of every sub-beams that passes through the multiple partial reflectors along the optical waveguides. Condition of constructive and destructive interference for the particular filtering optical wavelength could be adjusted by thermo-optic phase shifters of fine and wide tuning, placed along the beam expanders and the connecting waveguides, respectively. Rectangular ROADM arrangement (see **Fig. 2a**) is more compact, but it is strong polarization dependent that need polarization diversity [5]. Slanted arrangement (see **Fig. 2b, c**) provides better tuning rate ($\partial l/\partial T$ up to 0.6 nm/°C) [2, 5] and could provide low polarization dependence (PDL and PDF) by inserting additional polyamide half-plate for polarization rotation (PR).

The typical simulation (by FDTD) of MR-ROADM is shown in **Fig. 5, 6.** It proves that device could realize Drop/Through function. Better performances provides by the device with the large number of reflectors with variable reflector coefficients (see **Fig. 7a**). Simulation of this device (see **Fig. 7b**) has been done by the ray model and taking into account phase delays of all reflected and transmitted sub-beams. It proves that MR-ROADM can be implemented for 25 GHz or smaller ITU grids.

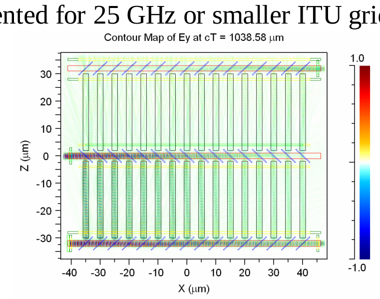


Fig. 5: Simulation of MR-ROADM at Drop wavelength.

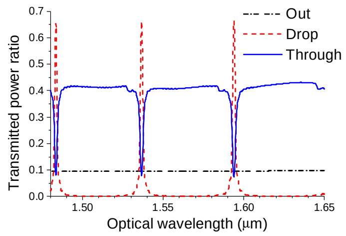
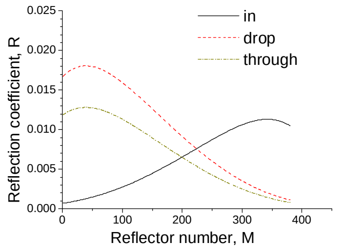
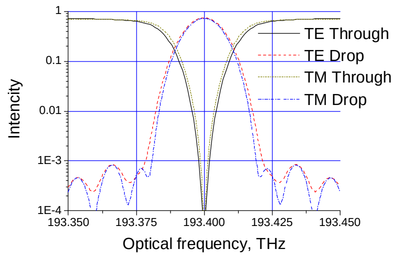


Fig. 6: Simulated frequency response of MR-OADM with 32 slanted reflectors (*j* = 45°). FWHM = 1.6 nm.



(a)



(b)

Fig. 7: Reflector coefficients apodization (a) and frequency response (b) of the 25 GHz slanted ROADM for two polarizations. Internal losses. TM: IL_D = –1.27 dB, IL_T = –1.31 dB; TE: are IL_D = –1.42 dB, IL_T = –1.46 dB.

III. Multi-reflection technology in thin SOI

Recently, two-dimensional grating [11] etched in a thin (220 nm) silicon-on-insulator waveguide had been used as a fiber-to-ridge waveguide coupler. This 2D grating is also perspective for multi-reflector technology as it provides additional possibility of polarization diversity without polarization rotators. This device is very compact and couples orthogonal modes from a single-mode optical fiber into two quasi-TE modes of two ridge waveguides that could be connected to the input/output of the photonic integrated circuit. The problem is that ridge waveguide has the dimension 220 nm by 10 µm that has multi-mode behavior which strongly disturbs device performances.

We propose new double waveguide design that is suitable for thin SOI devices. From the well-known paper by Soref et al. [12] one could derive simple relation between obtained changes in refractive index (*Dn*) and absorption (Δα) at the wavelength of interest (λ_0=1.55 µm) due to presence of free electron (N_e) and hole concentration (N_h) in silicon:

$$\Delta\alpha_e = 0.12\times|\Delta n_e| \qquad (1)$$
$$\Delta\alpha_h = 0.16\times|\Delta n_h|^{5/4}$$

Thus total change of complex refractive index due to the charge effect is:

$$\Delta n = \Delta n + jn', \qquad (2)$$

where $n' = \Delta\alpha\lambda_0/(4\pi)$, $\Delta n=\Delta n_h+\Delta n_e$, $\Delta\alpha= \Delta\alpha_h + \Delta\alpha_e$. From equation (1) one can see that if Δn<0.3 then the hole doping is more preferable as it provides smaller optical losses at the same index change with quality factor $|\Delta n_h|^{1/4}$. Thus we use p^+ doping for all structures discussed below.

Multi-mode behavior of thin ridge waveguides could be compressed by manufacturing heavily doped p^+ regions *Wg* on both sides of the Si-ridge of width *W*. One can see from data of **Fig. 8** that fundamental mode of such double waveguide has negligible losses related to the losses of the high order modes. Heavily doped p^+ regions could be also used for manufacturing the slanted reflectors of MR-ROADM (see **Fig. 2b**). Dependence of reflected and transmitted power for the incident angle 75^0 is shown in **Fig. 9**. Although the additional absorption losses are noticeable but they provides possibility to manufacture device with suitable performances.

Alternative method to manufacture partial reflectors for MR-ROADM design presented in **Fig. 2c** is based on the deep groove technology. For the case if quasi-TE mode incidents the reflector at close to the Brewster angle then reflective coefficient could be sufficiently small that will make possible to eliminate complex back filling of the groove by the material with appropriate refractive index. Results presented in **Fig. 10** shows for the case of nano-width groove the reflection coefficient could be variable in the appropriate range (see **Fig. 7a**) by changing the width and incline angle of the groove. One must mention that at Brewster angle the reflected filed is distorted and energy of fundamental mode is less than the total reflected power (due to the presence of high order modes). As it is shown on Fig.8 these modes decay due to the heavy doped regions of double waveguide.

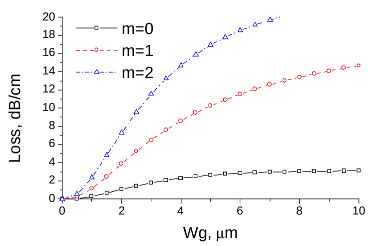


Fig. 8: Optical losses in double waveguide as a function of p^+-doped width *Wg*. Undoped width *W*=8, Dn_h=0.002.

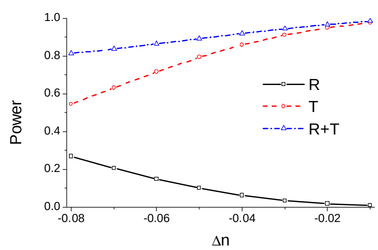


Fig. 9: Dependence of the power reflection and transmitting coefficients as a function of $\Delta n=\Delta n_h$.

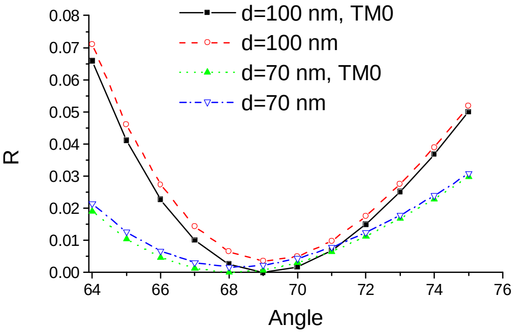


Fig. 10: Dependence of the power reflection as a function of the incident on the deep groove. Waveguide width 10 µm. Solid dots corresponds to the reflection to the fundamental TM_0 mode. 2D FDTD simulation.

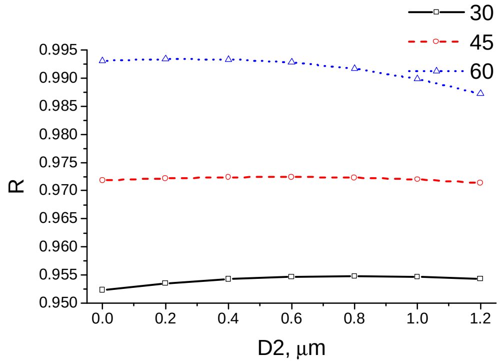


Fig. 11: Dependence of the corner reflection as a function of the waveguide shift (D2) at different incident angle.

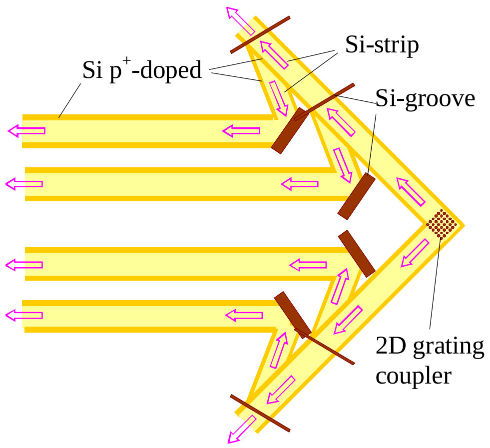


Fig. 12: General design of nono-scale SOI MR-ROADM.

MR-ROADM design presented on **Fig. 2c** needs implementation of small area bends. Deep grooves in double waveguide with heavy dopes sides provides very small optical losses for the large area of bend angles (see **Fig. 11).** All these provide the new designs of MR-ROADM that also utilize 2D-grating, heavy p^+-doping and nono-scale grooves. The part of this design is presented on **Fig. 12** and show the way to provide polarization diversity of the device.

Conclusions

The paper described recent results of theoretical investigation of the novel widely tunable reconfigurable optical add/drop multiplexers (ROADMs) and tunable filters employing multi-reflector beam expanders. It provides detailed description of devices based on Silicon-on-Insulator technology with thermo-optic tuning as well as the chalcogenide As_2S_3 glass on $LiNbO_3$ structures with acoustooptic tuning. A variety of different design architectures are described including a novel thin SOI double-waveguides for ROADM that utilizes nono-grooves and p^+-doping to provide better device manufacturability. Theoretical examination of multi-reflector filtering technology has been performed by appropriate application of finite difference time domain (FDTD) method, spectral approach and ray model (depending on the case study). Multiple numerical examples illustrate peculiarity of this new technology that provides wide tunability (within total C- or L-band) and remarkably high tuning rate (up to 0.6 nm/°C) without applying the Vernier principle. These kind of tunable filters and multiplexes are intended for flexible redirection of multi-hundred WDM wavelength channels in intelligence all optical networks with high dense ITU grid 25 GHz.

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