Design of 1x2 wavelength demultiplexer based on multimode interference

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The paper discusses the design and optimisation of the 1310/1550 nm multimode interference demultiplexer using the nanocrystalline diamond waveguide structure deposited on a silica-on-silicon substrate. The demultiplexer is designed by the beam propagation method and the simulation shows that for an optimised structure, the output energy of the fundamental mode is 79.3 % at a wavelength of 1310 nm and 76.3 % at 1550 nm. The designed demultiplexer will be suitable for harsh environmental conditions.

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1. Introduction

The importance of data transmission has been permanently growing as a consequence of the increased capacity and speed in the transporting and processing information needed for expanding new optical networks. New optical communication systems, such as Fibre to the Home, used not only for optical internet but also for videoconferencing, multichannel video services and etc., require the developing of novel photonic structures, which would allow high-speed signal processing. One of those, based on multimode interference (MMI) principles, is becoming ever more popular because of its many advantages like simple design, compact size and low insertion losses [1]. Optical communication systems often operate in a wavelength range of 1260–1560 nm due to the backbone optical networks formed by silica fibres, whose loss spectrum has two low-loss windows in the ranges of (i) 1200–1350 nm and (ii) 1450–1600 nm. Therefore, the MMI wavelength multi/demultiplexer (MUX/DEMUX) operating at wavelength channels of 1310 nm and 1550 nm has great potential.

Many different materials have been used for the design and realisation of photonic structures based on the MMI principle. Most of them are semiconductors like SiO_2-SiON [2], SiGe-Si [3], silicon-on-insulator SOI [4], and/or Si [5], but there are also several reports on MMI structures fabricated by ion exchange in glass [6, 7] or polymers [8, 9]. In our case, we used diamond thin films deposited on a silica-on-silicon substrate. The reason for that is that they possess a high refractive index and other suitable properties such as high thermal conductivity, Young's modulus, broadband transparency and excellent mechanical properties, as well as high chemical and thermal stability [10]. Moreover, such a waveguide structure makes it possible to realise ultra-compact MMI structures. An advantage of nanocrystalline diamond (NCD) used as a core optical layer comes from its easy fabrication process and excellent optical properties while the silicon substrate provides good compatibility with the silicon-based technology.

2. The design of single-mode waveguides

A cross-section view of the diamond thin film-based waveguide used for the design of a MMI demultiplexer (DEMUX) is shown in Fig. 1.

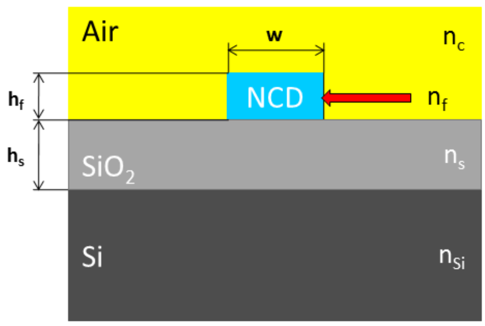

Fig. 1. A schematic cross-section view of the optical ridge waveguide used for a diamond-based 1310/1550 nm multimode interference demultiplexer.

The ridge waveguide used for DEMUX design consists of silica-on-silicon substrate and nanocrystalline diamond core waveguide. Prior to the actual design, refractive indices of the prepared optical layers were measured by dark-mode spectroscopy [11] using the Metricon 2010 prism-coupler. The obtained values of the refractive indices used for the design are summarised in Tabel 1.

Table 1. The values of the refractive indices of the applied materials measured by dark-mode spectroscopy that were used for the design of the diamond demultiplexer.

Wavelength (nm)	Refractive indices		
	n_{Si} * (-)	n_s - SiO_2 (-)	n_f - NCD (-)
473	4.468	1.464	2.437
632.8	3.882	1.457	2.412
964	3.609	1.451	2.398
1310	3.507	1.447	2.388
1550	3.476	1.444	2.386

*Since it is not possible to measure the refractive index of the silicon substrate by dark-mode spectroscopy, we used tabular values for our design (see http://refractiveindex.info/).

The design of single-mode ridge waveguides was done by modifying of the dispersion equation [12], which was refined by a 2D-beam propagation method using the BeamPROP™ software. The thickness (h_f) of the ridge optical waveguide layer were set to be a single-mode-guide at both operating wavelengths (1310 nm and 1550 nm). The thickness h_f of the diamond layer core optical waveguide film was calculated by using the following equation (1) [12]:

$$h_f = \frac{\lambda_0}{2\pi\sqrt{n_f^2 - n_s^2}}\left\{n\pi + arctg\left[p\sqrt{\frac{n_s^2 - n_c^2}{n_f^2 - n_s^2}}\right]\right\}. \qquad (1)$$

where λ_0 is operating wavelength, n is an integer number n = 0, 1, 2 …, and p is for the TE mode

$$p = 1. \qquad (2)$$

and for the TM mode

$$p = \left(\frac{n_f}{n_s}\right)^2. \qquad (3)$$

The minimal width w of the core waveguide was determined using the modify equation 1 in this case value of refractive index is $n_s = n_c$ and width w can be calculated by equation:

$$w = \frac{\lambda_0 \cdot k}{2\sqrt{n_f^2 - n_s^2}}. \qquad (4)$$

The dimensions of the waveguides were then specified by modelling with the RSoft software. Based on the simulation, the width w and the height h_f for the waveguide fundamental mode were set for both wavelengths (1310 nm and 1550 nm) to 350 nm.

The calculated effective refractive indices for fundamental modes are approximately 2.109 at 1310 nm and 2.047 at 1550 nm. The thickness of the SiO_2 buffer layer (h_s) was set based on the calculated one, which ensured that the out-coupled energy of the evanescent wave would be less than 1 % (this calculation procedure has already been described in [13]). Therefore, the thicknesses of the buffer SiO_2 layer h_s must be thicker than 933.4 nm or 1105.1 nm for 1310 nm and 1550 nm wavelengths, respectively. Then thickness h_s should be bigger than 1105.1 nm.

3. The design of the 1310/1550 nm multimode interference demultiplexer

A schematic view of the designed NCD demultiplexer (DEMUX) structure is shown in Fig. 2. The DEMUX consists of one input single-mode waveguide ($Port_{in}$) and a homogeneous multimode interference region connected to two output single-mode waveguides ($Port_{out1}$ and $Port_{out2}$).

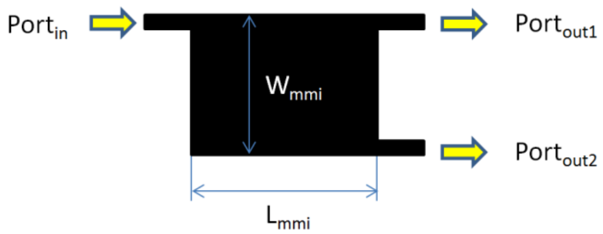

Fig. 2. The diamond structure of the MMI demultiplexer operating at the wavelengths of 1310/1550 nm.

This structure is based on the self-imaging effect of the propagation of an optical signal. Self-imaging is an optical property of multimode waveguides by which an input field profile is reproduced as single or multiple images at periodic intervals along the propagation direction of the waveguide [14-16].

The most common analytical method for the design of a MMI structure is a guided-mode propagation analysis [1]. Consider a step-index multimode slab waveguide with a width W_{mmi}. The waveguide supports M-guided modes with modal field profiles $\Phi_v(y)$ and propagation constants β_v, where $v=0$ .. $M-1$ is the mode number. It is assumed that radiation modes carry negligible power and therefore they can be neglected in this analysis. Consequently, the input field profile $\psi(y, 0)$ at the entrance of the multimode waveguide can be decomposed into the modal field distribution $\Phi_v(y)$ of all guided modes [14]. It can be found that certain lengths L_{mmi}, which at given wavelengths allow the splitting of the incoming optical radiation, interfere and give two single-mode separated waveguides. Such L_{mmi} can be approximately defined as:

$$L_{mmi} = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4 \cdot n_{core} \cdot W_{mmi}^2}{3 \cdot \lambda_0} \qquad (5)$$

where β_0 and β_1 are the propagation constants of the fundamental and first-order lateral modes, n_{core} is the effective refractive index, W_{mmi} is the width of the MMI part and λ_0 is the wavelength of the input signal, respectively.

4. The results of the design

The following will describe our process of designing the 1310/1550 nm diamond demultiplexer by a 2D BPM method with BeamPROP^{TM} software. The simulation was done for the width (w = 350 nm) of the input and output waveguides chosen so that the pertinent input and output waveguides (at 1310 and 1550 nm) would form a single mode waveguiding structure. The dimension of the width W_{mmi} was set to 2.4 µm. The modelling showed that the width should not be smaller or both output waveguides would behave as directional couplers. This is a very important condition to prevent the deterioration of the right function of the designed MMI DEMUX. Further, this width W_{mmi} eliminates the risk that the output waveguides would (as directional couplers) affect the output 1310/1550 nm signals. The maximum length L_{mmi} was optionally set to 30000 µm and alongside this length, we searched for all interference images with the aim to find the value of L_{mmi} as short as possible to ensure the lowest inserted loss of the whole structure.

Two cases of the DEMUX parameters were taken into account:

1. At DEMUX (1310/1550 nm, $Port_{out1}$=1310 nm, $Port_{out2}$= 1550 nm, see Fig. 3), we monitored the spreading of the signal having the wavelength 1310 nm towards the $Port_{out1}$ and another one having the wavelength 1550 nm towards $Port_{out2}$; here we searched for the L_{mmi} distance where the output energy for that actual wavelengths and output waveguides would be maximal.

2. At DEMUX (1550/1310 nm, $Port_{out1}$=1550 nm, $Port_{out2}$= 1310 nm, see Fig. 3), we did the same although, of course, in the opposite sense.

For both cases, we followed the strongest interferences. For them, we closely observed the crosstalks occurring at the output waveguides. The results are given in Table 2.

Table 2. The signals and crosstalks of the designed DEMUXes monitored at the strongest interferences.

Scheme 1: $Port_{out1}$= 1310 nm, $Port_{out2}$= 1550 nm				
Length L_{mmi}	Signal (%)		Crosstalk (%)	
(µm)	$Port_{out1}$ 1310 nm	$Port_{out2}$ 1550 nm	$Port_{out2}$ 1310 nm	$Port_{out1}$ 1550 nm
3532.2	60.3	60.3	28.7	4.1
17279.2	55.7	55.7	4.5	2.9
19080.3	72.1	72.1	5.5	2.9
21581.8	82.7	60.4	0.2	3.2

Scheme 2: $Port_{out1}$= 1550 nm, $Port_{out2}$= 1310 nm				
Length L_{mmi}	Signal (%)		Crosstalk (%)	
(µm)	$Port_{out2}$ 1310 nm	$Port_{out1}$ 1550 nm	$Port_{out1}$ 1310 nm	$Port_{out2}$ 1550 nm
50.7	79.3	76.3	0.3	1.6
1661.7	65.9	60.0	15.6	2.9
6739.0	59.3	59.3	2.3	2.7
10037.2	62.4	62.4	4.0	1.2
10812.35	61.8	61.8	0.3	0.9
21315.6	56.3	56.3	3.2	2.2

The most suitable options are further displayed as functions of the optical power on L_{mmi} lengths in Fig. 3.

The results presented can be described as follows:

Scheme 1a (DEMUX 1310/1550 nm, $Port_{out1}$=1310 nm, $Port_{out2}$= 1550 nm) for L_{mmi}= 3532.2 µm shows that the efficiency of both signals has reached 60.3 % (see Fig. 3a), but the crosstalk of $Port_{out1}$=1310 nm to output $Port_{out2}$ is unacceptably high (28.7 %, see Fig. 3b).

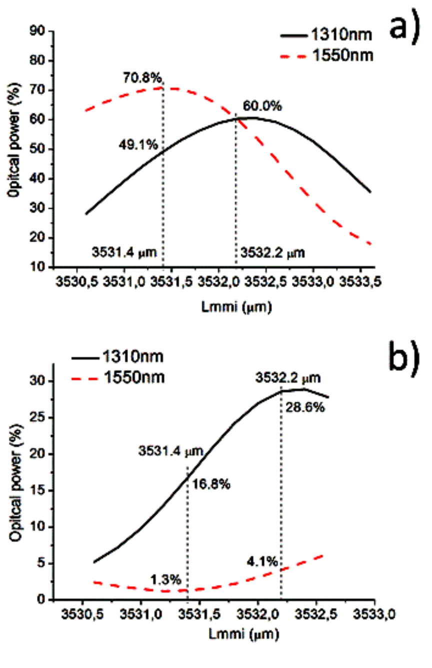

Fig. 3. The signals and crosstalks of the selected designed DEMUXes: Scheme 1 (DEMUX 1310/1550), a) signal L_{mmi}= 3532.2 µm, b) crosstalk L_{mmi}= 3532.2 µm.

Bearing in mind that the maximum value of the crosstalk should not exceed 6.0 %, the most interesting options would be the following:

Scheme 1b (DEMUX 1310/1550): L_{mmi} 19080.3 µm, where the output efficiency is 72.1 % and the pertinent crosstalk is 5.5 %, which is still smaller than the maximum allowed crosstalk value of 6.0 % (see Fig. 4a and 4b). Only a very small increase of the L_{mmi} value to 19080.8 µm on the one hand has increased the efficiency at the $Port_{out2}$= 1550 nm to 78.3 %; on the other hand, it has decreased the efficiency at the $Port_{out1}$= 1310 nm to 71.2 %. Moreover, the crosstalk value at the port $Port_{out2}$= 1310 nm has risen to unacceptable 7.1 %.

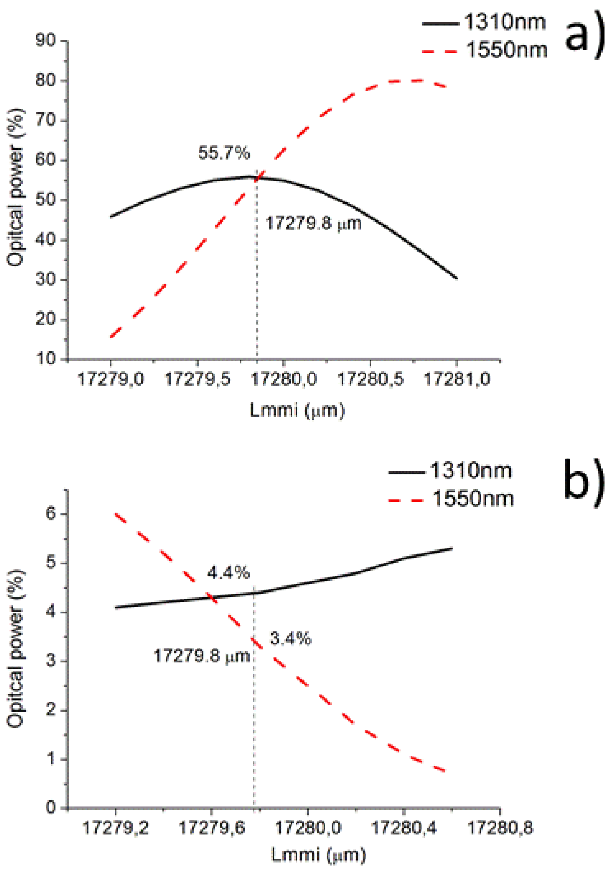

Fig. 4. The signals and crosstalks of the selected designed DEMUXes: Scheme 1 (DEMUX 1310/1550), a) signal L_{mmi}= 19080.3 µm, b) crosstalk L_{mmi}=19080.3 µm.

Scheme 2a (DEMUX 1550/1310): L_{mmi} 50.7 µm, where the output efficiencies are 79.3 % ($Port_{out2}$=1310 nm) and 76.3 % ($Port_{out1}$=1550 nm) and the crosstalks are lower than 1.6 % in both cases (see Fig. 5a and 5b). The output energies are not symmetrical here.

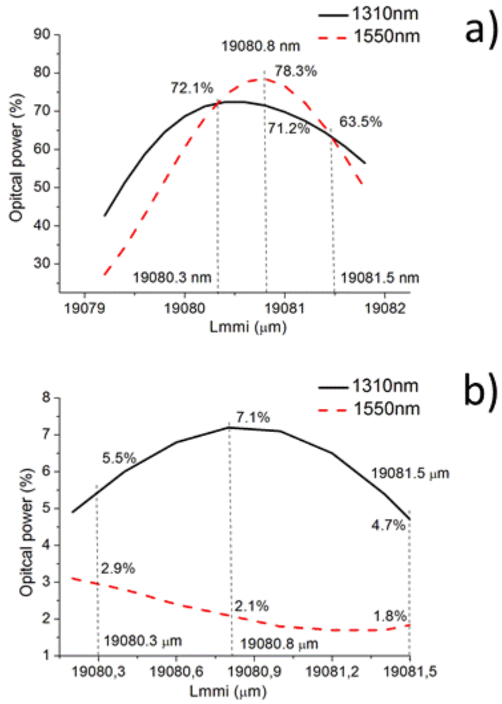

Fig. 5. The signals and crosstalks of the selected designed DEMUXes: Scheme 2 (DEMUX 1550/1310), a) signal L_{mmi}= 50.7 µm, b) crosstalk L_{mmi}= 50.7 µm.

Scheme 2b (DEMUX 1550/1310): Another suitable option is shown in Fig. 6a and 6b, where at L_{mmi} 10812.3 µm the total efficiency of 61.8 % is symmetrically divided and the crosstalks reach as low as 0.3 % ($Port_{out1}$=1310 nm) and 0.9 % ($Port_{out2}$=1550 nm).

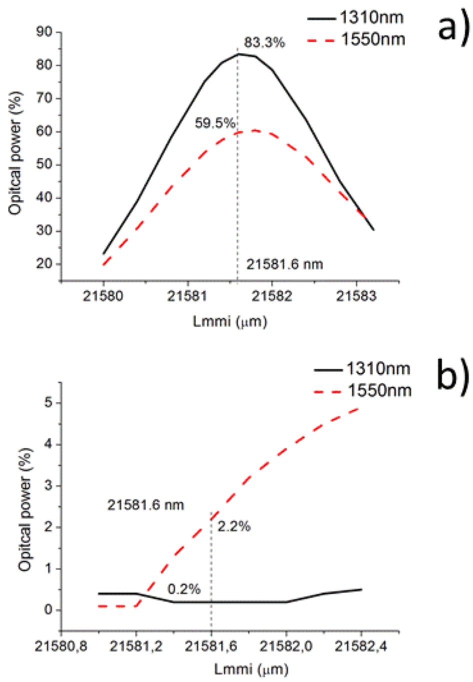

Fig. 6. The signals and crosstalks of the selected designed DEMUXes: Scheme 2 (DEMUX 1550/1310), a) signal L_{mmi}= 10812.35 µm, b) crosstalk L_{mmi}= 10812.35 µm.

The output amplitudes for both output waveguides are visible in Fig. 7, where Fig. 7a shows the output amplitudes for the DEMUX (1550/1310 nm, $Port_{out1}$=1550 nm, $Port_{out2}$= 1310 nm) with L_{mmi}= 50.7 µm and Fig. 7b shows the output amplitudes for the DEMUX (1310/1550 nm, $Port_{out1}$=1310 nm, $Port_{out2}$= 1550 nm) with L_{mmi}= 3532.2 µm. Fig. 7a illustrates the high efficiency of the designed DEMUX and a very low crosstalk of the signal 1550/1310 nm into the output ports. Fig. 7b clearly shows the strong crosstalk of the 1310 signal to the $Port_{out2}$ = 1310 nm.

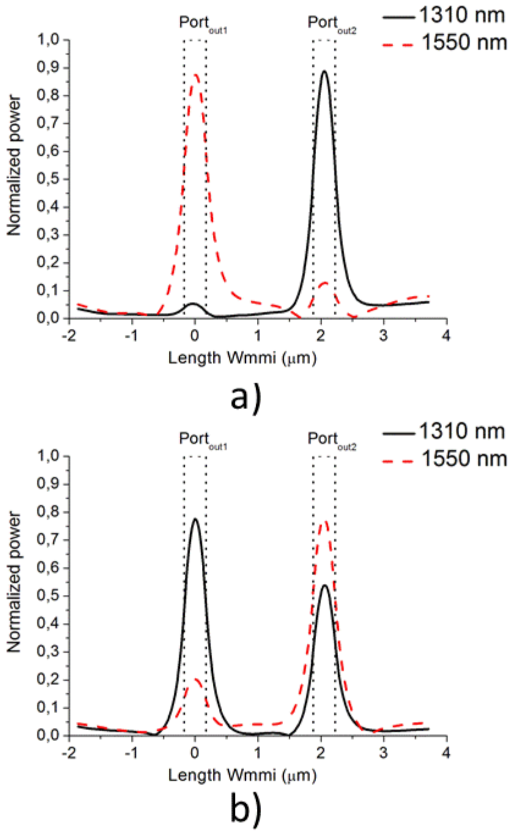

Fig. 7. Normalised output amplitudes for a) Scheme 2 (DEMUX 1550/1310), $Port_{out1}$=1550 nm, $Port_{out2}$= 1310 nm with L_{mmi}= 50.7 µm and b) Scheme 1 (DEMUX 1310/1550), $Port_{out1}$=1310 nm, $Port_{out2}$= 1550 nm with L_{mmi}= 3532.2 µm.

Finally, we determined the fabrication tolerances of the designed DEMUX devices by modelling them with respect to the refractive indices of the diamond waveguide layer n_f, silica buffer layer n_s, and also the thickness of the h_f waveguide and its dimensions (the length L_{mmi} and the width W_{mmi}). The results obtained may be summarised as follows:

- Changing the refractive index within ± 0.003 decreases the efficiency down to 0.5 %.
- Changing the dimensions of the ridge waveguide (w = 350 nm) ± 10 nm is followed by an efficiency decrease down to 3.0 %.
- Broadening the W_{mmi} width by 10 nm lowers the efficiency to 10 %. Narrowing the W_{mmi} width means a significant deterioration of the DEMUX function. Because of small dimensions, i.e. a short distance of the output waveguides, the waveguides start to behave as directional couplers. Consequently, the energy of the 1310 and 1550 nm signals would pour from one output to another and the whole DEMUX is not fully functional.
- Changing the L_{mmi} by ± 100 nm should decrease the efficiency of the output signal to 5.0 % and also increase the crosstalk up to 0.5 %.

5. Conclusions

We have proposed a wavelength NCD demultiplexer based on multimode interference couplers operating at the wavelengths of 1310 nm and 1550 nm. The diamond DEMUX was designed by using RSoft software based on the beam propagation method.

Firstly, the single-mode diamond thin film waveguides deposited on a silica-on-silicon substrate were calculated. The simulation showed that the height h and the width w of the input and output of the single-mode diamond waveguides have to be 350 nm and the thickness of the SiO_2 buffer layer h_s has to be at least 1105 nm in order to ensure that the out-coupled energy of the evanescent wave would be less than 1 % for both wavelengths (1310/1550 nm).

Secondly, the multimode interference part was designed. The multimode part width W_{mmi} was set to 2.4 µm. This width eliminated the risk that the output waveguides would (as directional couplers) affect the outputs of the 1310/1550 nm wavelength signals. The maximum length L_{mmi} was optionally set to 30000 µm; alongside this length, we looked for all interference images. The most effective interference (length beat) was found for the length of L_{mmi}= 50.7 µm (DEMUX 1550/1310 nm, $Port_{out1}$=1550 nm, $Port_{out2}$= 1310 nm, Scheme 2a**)**, where the output energy of 79.3% for $Port_{out2}$= 1310 nm and 76.3% for $Port_{out1}$= 1550 nm with very low crosstalk (0.3% for $Port_{out1}$=1310 nm and 1.6% for $Port_{out2}$=1550 nm) were achieved.

The designed structure can be used for a DEMUX in a harsh environment that would require a very good thermal and chemical stability of the device.

Acknowledgements

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