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Y. Zhang, M. Schneider, D. Karnick, L. Eisenblätter, T. Kühner, M. Weber, "Low-loss and robust DWDM Echelle grating (de-)multiplexers in SOI technology," Proc. SPIE 10914, Optical Components and Materials XVI, 109140J (27 February 2019); doi: 10.1117/12.2507433

Event: SPIE OPTO, 2019, San Francisco, California, United States

Low-Loss and Robust DWDM
Echelle Grating (De-)Multiplexers in SOI Technology

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ABSTRACT

Driven by the increasing demands of ultra-broad bandwidth transmission in telecommunications as well as in large-scale scientific experiments, interests in developing on-chip DWDM networks based on silicon photonics is increasing rapidly. With compact structures, low loss and robust fabrication, Echelle grating (EG) (de-)multiplexers become one of the key components. Two competitive design methods are the Rowland circle (RC) and the two stigmatic points (TSP) method, with the latter one offering remarkable advantages on optical aberrations and degrees of freedom.

We demonstrate a self-developed design kit for both methods involving MATLAB calculation, COMSOL Multiphysics simulation and GDSII layout. In our kit, several parameters are reserved to optimize the geometry in terms of device footprint, reflector configurations etc..

By making rigorous simulation on an HPC cluster, we obtained well-performing, robust and compact EG (de-)multiplexers based on the two stigmatic points method. For the 7-channel, 9th diffraction order and 800 GHz channel spacing device, we get a simulated average optical loss of 2.3 dB and a crosstalk of less than -20 dB with an on-chip footprint of $400 \times 690\ \mu m^2$.

Our silicon-photonic devices were fabricated on a 250 nm silicon-on-insulator (SOI) platform using e-beam lithography and dry etching. The comparison between measurement results of fabricated devices and simulation results was carried out, as well as a comparison between designs based on both design methods. Additionally, the experimental result of a 25-channel (de-)multiplexer with 200 GHz channel spacing in the C-band is presented to study the performance of the TSP method for a narrow channel spacing and large footprint design.

Keywords: (De-) Multiplexer, Two stigmatic points (TSP), Rowland circle (RC), wavelength division multiplexing (WDM), SOI, COMSOL Multiphysics.

1. INTRODUCTION

With the rapid development in SOI technology, on-chip high-bandwidth networks (OCHBN) are becoming feasible and raising more and more research interest. Besides, the research driving force for OCHBN also comes from particle physics and photon science. For future detector systems in fundamental and applied research, a huge amount of data is being generated and has to be transmitted to data processing, for which, a high bandwidth transmitter based on wavelength division multiplexing (WDM) systems and SOI technology is a promising solution [1].

WDM systems based on conventional glass waveguide technology have achieved much success, while constructing a compact, robust and low-loss WDM system in SOI technology is still a challenge. There are mainly four ways to construct on-chip WDM systems, they are ring resonators, lattice-form filters, arrayed waveguide gratings and planar concave gratings (also called Echelle gratings (EGs)), respectively [2]. In comparison, the EGs have the weakest sensitivity to local process variations since light mainly travels in the free space region and slab waveguide instead of being confined by waveguides laterally, and thereby lowering the dependency on chip fabrication dramatically.

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Optical Components and Materials XVI, edited by Shibin Jiang, Michel J. F. Digonnet,
Proc. of SPIE Vol. 10914, 109140J · © 2019 SPIE · CCC code: 0277-786X/19/$18
doi: 10.1117/12.2507433

Presently, there are two popular methods to design planar EG (de-)multiplexers, namely the Rowland circle (RC) and the two stigmatic points (TSP) method. The RC method has been widely investigated, a detailed study with favorable results is given in [3], while the latter one has been reported rarely since being proposed by IBM in 2008 [4]. We developed a design kit integrating both methods, with which we accomplish designs of EG (de-)multiplexers based on each method. A number of simulation and experimental results will be shown in this paper.

2. DESIGN KIT OF EG (DE-)MULTIPLEXERS

The design kit involves two types of software, which are MATLAB and COMSOL Multiphysics with WaveOptics module. The complete design flow is illustrated in figure 1, starting from EG geometry calculation in MATLAB where both of the abovementioned design methods are available. And, depending upon the user's choice, the program calculates the EG geometry accordingly. The configuration parameters for two methods vary a lot while the key parameters are similar including the material and thickness of the core layer, the materials of claddings, the diffraction order and the reflector type of the grating elements. More detailed parameters will be discussed in the following sections.

The second step is to generate the equivalent simulation model for COMSOL Multiphysics. Since the calculated EG geometry is usually rather complex with many grating elements and different tilt angles for each set of elements, it is hard to construct a simulation model directly in COMSOL. Instead, MATLAB is invoked by COMSOL via the LiveLink^{TM} module [5]. In this way, the geometry calculated by the MATLAB program as well as additional simulation parameters can be directly transferred to COMSOL.

One key hardware requirement for running the simulation of EGs is large-size memory since the FEM solution of an EG (de-)multiplexer with a footprint of 10^4 μm^2 easily consumes several hundreds of gigabytes of memory. In consequence, a small geometry in design is always recommended. In addition, it is beneficial to perform 2D simulations instead of 3D simulations in most cases; as long as the simulation module is configured with correct boundary conditions, 2D simulations can give accurate enough results. One characteristic example about making 2D waveguide simulation with WaveOptics module is [6].

All the devices shown in this paper were simulated by a high-performance computing cluster at the Karlsruhe Institute of Technology on special fat nodes with 1 TB memory. Based on the simulation results, users can optimize the design further by adjusting the design parameters and repeat simulations until the desired results are obtained.

The final step of the process is to generate the device layout for foundries by generating a GDSII file from the generated geometry.

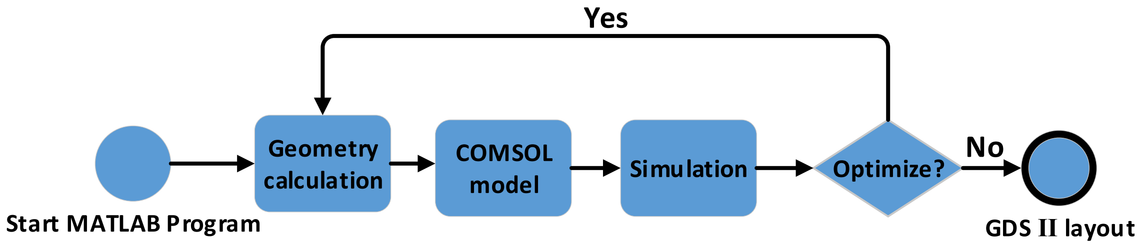

Figure 1. Design flow for generating Echelle grating (de-)multiplexers.

3. ROWLAND CIRCLE DESIGN METHOD

The Rowland circle method to design Echelle gratings was discovered by Henry Rowland in the late 19th century [7]. A standard Rowland mounting is made up of two circles where the small circle is named Rowland circle (RC) with a radius of R, and the larger one is named grating circle (GC) with a radius of 2R. By placing the RC inside the GC and making them tangent at a random point, the required geometry is obtained as shown in figure 2. The input and output channels are placed along the RC and the grating elements are along the GC circumference, resulting in the diffraction gratings. The longer the grating line is, the more grating elements can be placed.

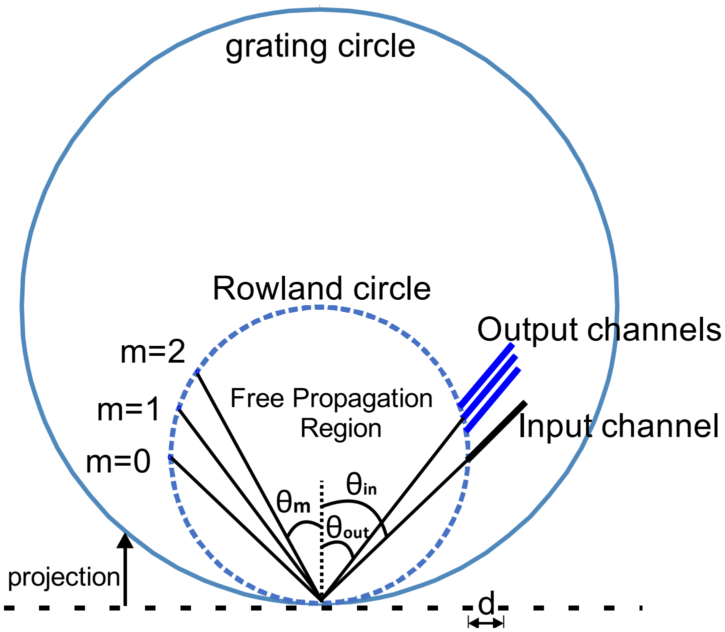

Figure 2. Schematic drawing of the standard Rowland mounting.

Two crucial parameters for the RC method are diffraction order m and grating period d, the corresponding definitions can be found in figure 2. Normally, to complete a design, additional parameters are required, including the operating wavelength range in free space ($\lambda_{\min} \sim \lambda_{\max}$), the central wavelength of the central output channel $\lambda_{central}$, the input angle θ_{in}, the angle of the central output channel θ_{out}, the number of output channels N and the length of the grating line L. From [3], the diffraction equation can be written as:

$$d(\sin\theta_{in} + \sin\theta_{out}) = \frac{m\lambda}{n_{eff}} \tag{1}$$

where n_{eff} is the effective refractive index of the core material at the incident wavelength. Considering the central output wavelength as the reference wavelength, the grating period d can be calculated from formula (1):

$$d = \frac{m}{\frac{n_{eff}}{\lambda_{central}}(\sin\theta_{in}+\sin\theta_{out})} \tag{2}$$

With the help of formula (2), the coordinates to place grating elements can be determined. To place a wide reflector as grating element, some border conditions have to be taken into account, especially the tilt angle of each reflector. The method to design the tilt angle of the reflectors can be found in [3]. Additionally, based on formula (1), the angular dispersion can be derived as [8]:

$$\frac{d\theta}{d\lambda} = \frac{(\sin\theta_{in}+\sin\theta_m)}{\lambda\cos\theta_m} \cdot \left(1 - \frac{\lambda}{n_{eff}}\frac{dn_{eff}}{d\lambda}\right) \tag{3}$$

where θ_m is the output angle at diffraction order m. Given the operating wavelength of output channels is designed to have equidistant intervals, the operating wavelength difference between adjacent output channels can be calculated:

$$\Delta\lambda = \frac{\lambda_{\max}-\lambda_{\min}}{N-1} \tag{4}$$

Then, the angle of output channels can be determined based on formula (3) and (4).

4. TWO STIGMATIC POINTS DESIGN METHOD

The TSP method is proposed by IBM [3] mainly by making use of the ellipse property:

$$F_1A + F_2A = 2l \tag{5}$$

Where, points F_1 and F_2 are the focuses of an ellipse, point A is a random point on the ellipse and l is the length of ellipse major axis. Now, imagining waveguide channels of EG (de-)multiplexers are a set of points: point O in figure 3 corresponds to a common input waveguide channel, points A and B correspond to two output channels with different operating wavelengths (λ_1 for channel A and λ_2 for channel B). The effective wavelengths of λ_1 and λ_2 are λ_{eff1} and λ_{eff2}, respectively. Then an ellipse E1 can be drawn based on focal points O and A, and with $2l_1 = \lambda_{eff1}$. Similarly, ellipse E2 is drawn based on the focal points O and B, and with $2l_2 = \lambda_{eff2}$. Ellipses E1 and E2 intersect at point P_1. In the same way, a set of ellipses can be drawn successively with $2l_1 = \lambda_{eff1} \times m \times N$ and $2l_2 = \lambda_{eff2} \times m \times N$ where N = 2, 3… and m is the diffraction order. For each N we get an intersection point, as a result we get points P_2, P_3… P_n. These points P_1, P_2… P_n are the coordinates to place gratings elements. To calculate the coordinates of the residual output channels, circles with radius $R_n = \lambda_{neffx} \times m \times N - OP_n$ (λ_{neffx} is the effective wavelength for channel x) are drawn successively by regarding the grating element positions as the center. The resulting intersections give an area to place output channels. With above information, we can construct a preliminary geometry, further optimization can be made based on simulation results.

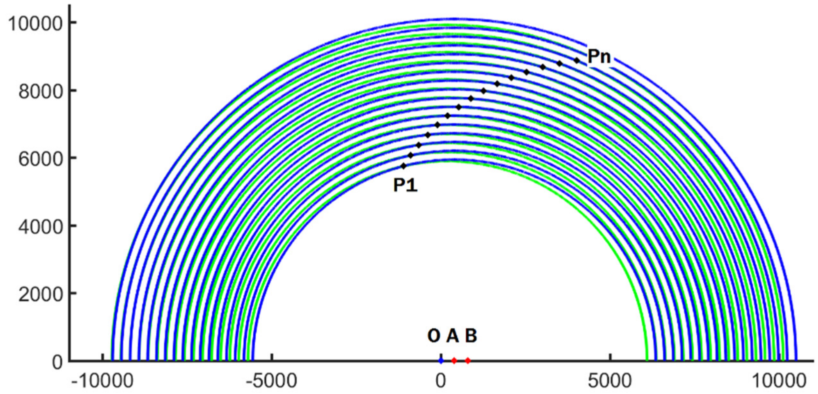

Figure 3. Schematic of two stigmatic point based (de-)multiplexer design method.

5. ECHELLE GRATING (DE-)MULTIPLEXERS

By use of the above design kit, several EG (de-)multiplexers were designed and will be show in this section. They were fabricated at IMS-CHIPS (Institut für Mikroelektronik Stuttgart, Germany) on a 250 nm SOI platform using e-beam lithography and dry etching. The top crystalline silicon layer and buried silicon dioxide are 250 nm and 2 µm thick, respectively. For all the devices in the following section, the grating elements are designed to be Bragg reflectors [8] and the diffraction order is set to be 9^{th}. Additional n++ doped regions are placed along the side borders of (de-)multiplexers, working as absorbers for stray light. For device characterization, we use a tunable laser module Agilent 81689A from device Agilent 8163B Lightwave Multimeter with a wavelength range from 1524 nm to 1576 nm.

5.1 Influence of stray light absorbers

The n++ doped absorbers are designed to attenuate stray light and avoid undesired interference. An EG (de-)multiplexer GM1 was designed based on RC method with the side borders attached. Figure 4 and Figure 5 are the corresponding GDSII layout and microscope pictures, respectively. GM1 has 5 output channels with a channel spacing of 1600 GHz (12.97 nm) and a footprint of approximately 100×330 μm^2 (measured without I/O waveguides and grating couplers). The design parameters of this device are: R = 180 µm, $\theta_{in} = 46°$, $\theta_{out} = 42°$, operating wavelength range (1527.22nm ~ 1578.69nm), $\lambda_{central}$ = 1552.52nm and L = 160 µm.

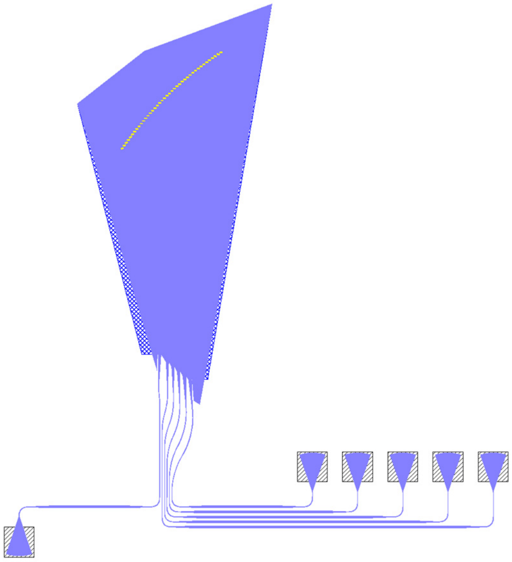

Figure 4. GDSII layout of EG GM1.

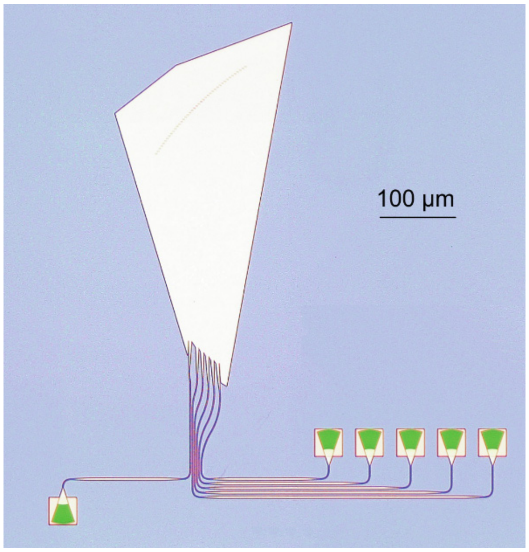

Figure 5. Microscope picture of EG GM1.

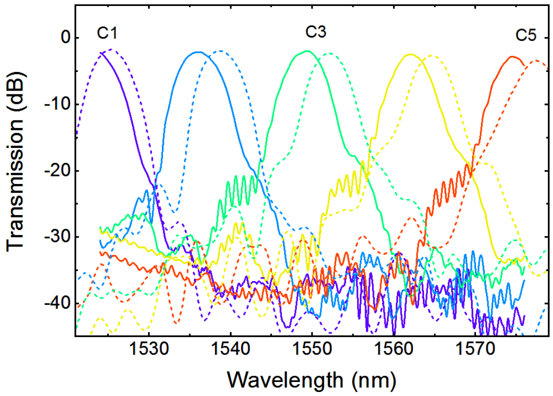

Figure 6. Simulated (dots) and measured (line) transmission spectrum of EG GM1.

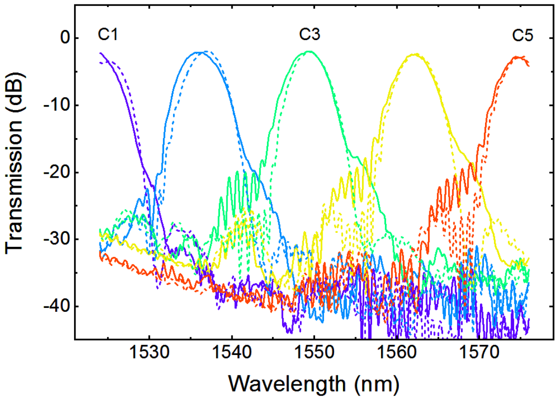

Figure 7. Measured transmission spectrum of EG GM1 (line) and EG GM2 (dots).

Figure 6 shows the simulated and the measured transmission spectrum of device GM1. A comparison of the results shows that the measured transmission spectrum of central output channel experiences a blue shift of 2.74 nm compared to the simulated, while the optical loss of each peak matches perfectly. We suspect a thicker silicon layer compared to the thickness used in the simulation and a non-ideal SiO_2 cladding layer as main reasons for the wavelength shift.

The measured maximum channel crosstalk of GM1 is -26.3 dB, appearing at channel 1 (C1) at 1524 nm and the average optical loss of the entire device is as low as 2.3 dB. Overall, for small footprint and large channel spacing, the RC method offers decent designs and the simulations approach the measurements closely.

A second design GM2 is identical to GM1 but without absorbers. A comparison of the measured transmission spectrum of GM1 and GM2 is given in figure 7. In comparison to GM1, the transmission spectrum of GM2 shifts slightly by 0.50 nm to bigger wavelengths. Nevertheless, this wavelength shift can't be simply attributed to the influence of stray light as the optical loss of both devices nearly remains the same. The phenomenon can be induced by local variations of the silicon layer thickness and other process variations. The maximum channel crosstalk of GM2 is -26.0 dB which is 0.3 dB higher than GM1, but still in the same range. According to the above comparison, the effect of side borders is slightly for wide channel spacing devices.

5.2 RC and TSP based Echelle grating (de-)multiplexers

The robustness of EG (de-)multiplexers design method is hard to be verified by devices at a wide channel spacing with large peak widths. For this reason, we construct several more characteristic devices with narrower channel spacing and simultaneously compare the performance of devices designed based on two design methods. The microscope picture of EG EM1 and GM3 illustrated in Figure 8 and Figure 10 are designed based on TSP and RC method, respectively with the same channel spacing of 800 GHz (6.85nm) and the same central wavelength of 1552.52nm. While GM3 has 19 output channels, a remarkably larger number than that of EM1. This is because our previous EG devices designed based on RC method experienced significantly large wavelength shifts. To ensure that there are enough channels lying in available measurement range (1524nm ~ 1576nm), we make many redundancy channels.

Since the design parameters for two methods are very different, it is hardly possible to design 'identical' geometries. But by adjusting the parameters moderately, the designs can be made quite similar. GM3 has an operating wavelength ranging from 1496.72 nm to 1612.65 nm and the additional design parameters are set as: R = 250 µm, $\theta_{in} = 48°$, $\theta_{out} = 42°$ and L = 340 µm. EM1 has only 7 channels with an operating wavelength ranging from 1533.47 nm to 1572.06 nm and the additional parameters for EM1 are set as: input channel fixed at (0 µm, 0 µm), channel 1 fixed at (9 µm, 0 µm), channel 7 fixed at (39.8 µm, 0 µm) and 2*l* ranges from 398 µm to 716.4 µm. The resulting footprint of EM1 is 400×690 μm^2 and of GM3 is 245×520 μm^2.

Figure 8. Microscope picture of EG EM1.

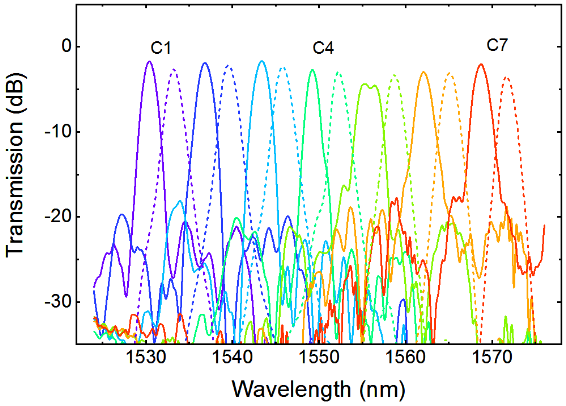

Figure 9. Simulated (dots) and measured (line) transmission spectrum of EG EM1.

According to the simulation and measurement results of EM1 shown in Figure 9, the average optical loss of 7 channels is 2.4 dB (almost the same with simulation result of 2.1 dB) and the maximum channel crosstalk is -23.0 dB, appearing at channel 2 which coincides well with the simulations (dotted lines). A comparison of simulation and experimental results shows a blue shift of 3.27 nm for central output channel, which is almost half of the channel spacing, but in the same range with the deviation from GM1.

Figure 10 is a comparison between simulation and measurement results of device GM3. GM3 doesn't show so nice transmission spectrum as EM1, one channel (C11) behaves like 'broken' channel and has an optical loss as high as 9 dB, a significantly higher value than that of other channels (2.3 dB in average). Nevertheless, the average optical loss is similar to the simulation result (2.4 dB) if without taking channel 11 into account. The source of this drop can be a fabrication problem and is under investigation. For an examination, the upper cladding layer of GM3 will be removed and further study will be done by means of electron beam microscopy. The maximum channel crosstalk for device EG GM3 is -21.7dB, appearing at channel 8 at 1536.50 nm. Overall, the optical loss of two devices has a similar value but the crosstalk of GM3 is 2.3 dB higher than that of EM1. Additionally, both devices experience wavelength blue shift similar to device

GM1, and the shift value is 1.67 nm for GM3 and 3.27nm for EM1 respectively. The comparison of two devices based on different design methods shows that it is easier to design small devices with many channels using the RC method. In our design, for a channel spacing of 800GHz, RC method based device experiences smaller wavelength shift than the TSP method based device and both devices show similar performance except for a slightly higher crosstalk for RC method based device.

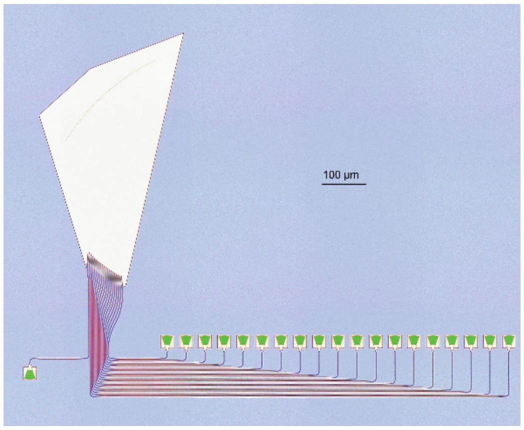

Figure 10. Microscope picture of EG GM3.

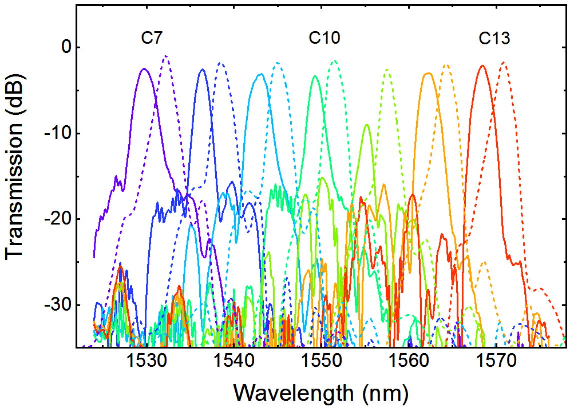

Figure 11. Simulated (dots) and measured (line) transmission spectrum of EG GM3.

5.3 A 25-channel 200-GHz Echelle grating (de-)multiplexer based on the TSP design method

To study the in-depth performance of the TSP method, a more complex device was designed and fabricated. As illustrated in figure 12, we developed a 25-channel device, EG EM2, with a significantly narrow channel spacing of 200 GHz (1.64 nm). The central wavelength λ_{central} of EM2 is 1549.32 nm and the operating wavelength ranges from 1530.33 nm to 1568.77 nm. The additional parameters of EM2 are set as: input channel fixed at (0 μm, 0 μm), channel 1 fixed at (9 μm, 0 μm), channel 25 fixed at (100 μm, 0 μm) and $2l$ ranges from 400 μm to 1400 μm. The resulting on-chip footprint of device EM2 is 845×1290 μm^2 (without the I/O waveguides and grating couplers).

Since the geometry of EG EM2 is too large to simulate, only the measurement result is presented in this section. Figure 13 shows the measured transmission spectrum of EM2. The most eye-catching phenomenon is the strong drop of the transmission peak from channel 12, 14, 15 and 16, similar to the drop occurred on device EG GM3 in section 5.2. As can be seen, the optical losses of these 'broken' channels are higher than 7 dB. While in comparison, the average optical loss of the residual channels is as low as 3.5 dB and the best channel reaches 2.3 dB (channel 1). The maximum channel crosstalk of device EM2 appears at channel 8 with a value of 11.3 dB at 1538 nm and the average value of all these 'usable' channels is 15.7 dB. Additionally, the wavelength shift of the central output channel for this device is 2.37 nm, still in the same range as for that of EM1 shown in section 5.2.

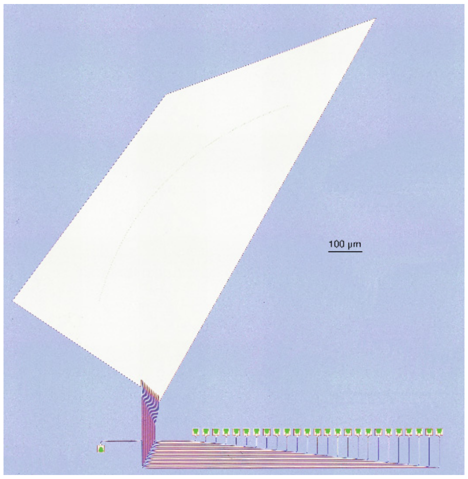

Figure 12. Microscope picture of EG EM2.

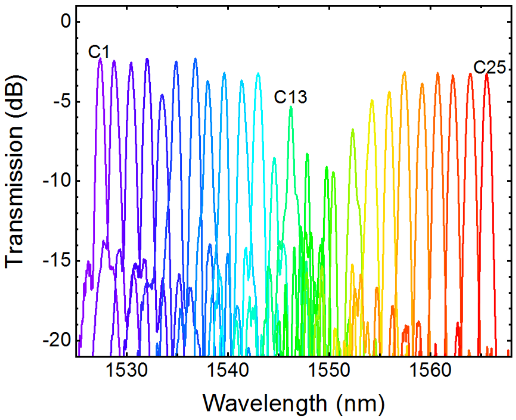

Figure 13. Measured Transmission spectrum of EG EM2.

6. CONCLUSION

In this paper, we presented our self-developed EG (de-)multiplexer design kit integrating two EG (de-)multiplexer design methods which are the Rowland circle method and two stigmatic points method, respectively. The design flow required to accomplish a final layout is illustrated. Based on our design kit we designed and fabricated a passive chip including a set of devices on a 250 nm SOI platform. According to the simulation and measurement results of device GM1 and GM2, we found the performance of two devices are nearly identical including the optical loss and the channel crosstalk. The comparison of different design methods based on devices EM1 and GM3, shows the obvious advantages of RC method in designing multiple channels with narrow channel spacing but smaller devices. The measured optical loss of EM1 and GM3 match simulation result remarkably well, both are lower than 2.5dB. The crosstalk of GM3 is -21.7dB, 2.3dB higher than that of EM1, while both values are acceptable. At the end of this paper, a more complex device EM2 with 25 channels and 200 GHz channel spacing was presented. For such a narrow channel spacing device based on the TSP design method, the performance is not good enough as the optical loss and crosstalk is significantly higher than for the devices presented in section 5.1 and 5.2. The reason for the seen blue shifts may be manifold and require in-depth investigations. Based on the study in this paper, our design kit shows promising potential in robust EG (de-)multiplexer design, while there is still room for optimizations for more advanced designs.

ACKNOWLEDGEMENT

This research is supported by the program Matter and Technology of the Helmholtz Association, Germany and the China Scholarship Council (CSC), China.

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