

# Development of a slow-light spectrometer on a chip

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## ABSTRACT

We discuss the design and development of a slow-light spectrometer on a chip with the particular example of an arrayed waveguide grating based spectrometer. We investigate designs for slow-light elements based on photonic crystal waveguides and grating structures. The designs will be fabricated using electron-beam lithography and UV photolithography on a silicon-on-insulator platform. We optimize the geometry of these structures by numerical simulations to achieve a uniform and large group index over the largest possible wavelength range.

**Keywords:** slow light, spectrometer, photonic crystal

## 1. INTRODUCTION

Enormous effort has been applied over recent years in developing lab-on-a-chip systems for a wide range of applications including for example, drug discovery in pharmaceutical industries, detection of biohazards, and point of care diagnostics.<sup>1-4</sup> Integrated photonic devices of various functionalities are core components of such systems since they not only offer a reduced footprint and improved cost performance, but are also readily compatible with the fabrication process. In particular, an important component is a high-resolution spectrometer since it enables on-chip spectral analysis. A wide variety of miniature on-chip spectrometers have been recently demonstrated.<sup>2</sup> Some of these are based on dispersive components and include arrayed waveguide gratings (AWG) spectrometer,<sup>3,5,6</sup> grating spectrometers<sup>7</sup> and superprism-based spectrometers.<sup>8</sup> The main challenge of these types of integrated spectrometers is the trade-off between the spectral resolution and the size of the structure.

Slow- and fast-light technology<sup>9</sup> has recently attracted a great deal of interest, both in terms of fundamental and practical aspects.<sup>10-12</sup> It has recently been shown that slow light can be used to enhance the performance of various types of spectroscopic interferometers.<sup>13-16</sup> In particular, it has been demonstrated that, by changing the width of channel waveguides that form the array of dispersive elements in an AWG spectrometer, one can enhance the group index and hence the spectral resolution of the AWG spectrometer.<sup>5</sup>

In this paper, we explore the use of dispersive elements based on slow light to build on-chip miniaturized AWG spectrometers with very high spectral resolution. We investigate different designs depending on the fabrication techniques available: photonic crystal waveguides using electron-beam lithography and one dimensional (1-D) periodic grating structures using deep-UV photolithography, both on a silicon-on-insulator (SOI) platform. The goal is to optimize the geometry of these structures to achieve a uniform and large group index over the largest possible wavelength range.

## 2. DESIGN OF THE GEOMETRY OF AN ON-CHIP SPECTROMETER

There are many different geometries that can be applied to construct an on-chip spectrometer, such as Mach-Zehnder interferometer, etched diffraction grating,<sup>17,18</sup> arrayed waveguide grating,<sup>19</sup> and so on. Here, we study the case of an AWG as an illustrating example.

A conventional AWG is typically comprised of three parts<sup>20,21</sup> as shown in Figure 1. The input signal field first propagates through a free-propagation region (FPR) to expand its beam width. The field is then coupled

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into a series of waveguides. The waveguides are designed such that the lengths of neighboring waveguides differ by a fixed amount  $\Delta l = m\lambda_0/n_{\text{eff}}$  where  $\lambda_0$  is the designed central (vacuum) wavelength of the device, and  $n_{\text{eff}}$  is the effective index (i.e., mode index) of the waveguides. The output ports of these waveguides are spaced periodically (with a period of  $\Lambda$ ) at the entrance to a second FPR, and the fields exiting from the waveguide array will constructively interfere and focus at the other side of the second FPR.

The diffraction equation of such an AWG is given by

$$n_{\text{wg}}\Delta l + n_{\text{FPR}}\Lambda(\sin\theta_{\text{inc}} + \sin\theta_{\text{diff},m}) = m\lambda, \quad (1)$$

where  $n_{\text{wg}}$  and  $n_{\text{FPR}}$  are the effective indices for the waveguides and the FPR, respectively.

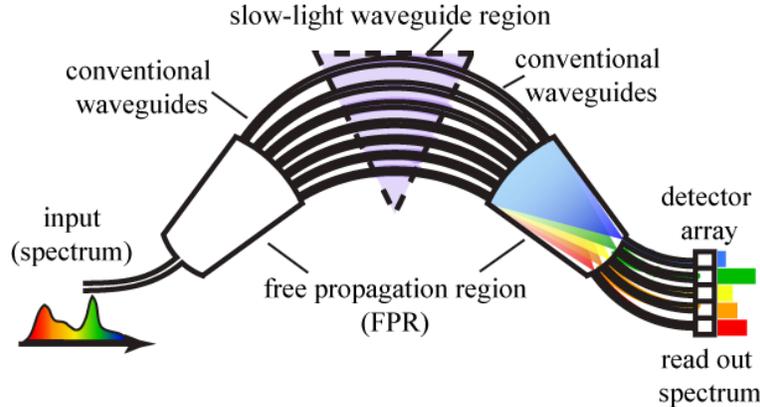


Figure 1. Schematic diagram of a slow-light arrayed waveguide grating spectrometer.

Next, we consider an ideal slow-light medium with the refractive index of the form of

$$n(\nu) = n_0 + \frac{n'_g}{\nu_0}(\nu - \nu_0), \quad (2)$$

where  $n'_g = n_g - n$  is the reduced group index of the medium in the vicinity of the center frequency  $\nu_0$ , and where  $n_g = n + \nu \, dn/d\nu$  is the group index of the medium.

Now consider the case in which the AWG consists of a slow-light waveguide region as shown in Figure 1 such that the group index of the slow-light waveguides is given by  $n_{g,\text{wg}}$ .

In practice, an AWG can work in a configuration such that the diffraction angle for the central wavelength is zero degrees to minimize the influence of aberrations, etc. In such cases, the diffraction order  $m$  of the AWG depends primarily on the waveguide increment  $\Delta l$  such that  $m \approx n_{\text{wg}}\Delta l/\lambda$ , and the angular dispersion is given by<sup>21</sup>

$$\frac{d\theta_{\text{diff},m}}{d\lambda} \approx \frac{n_{g,\text{wg}}\Delta l}{n_{\text{FPR}}\lambda\Lambda \cos\theta_{\text{diff},m}} \quad (3)$$

$$= \frac{n_{g,\text{wg}}m}{n_{\text{FPR}}n_{\text{wg}}\Lambda \cos\theta_{\text{diff},m}}. \quad (4)$$

One sees that by using a slow-light waveguide array, the angular dispersion of an AWG can be enhanced by a factor of  $n_{g,\text{wg}}/n_{\text{wg}}$ , and therefore one can enhance the spectral resolution by the same factor.

Here, we demonstrate our design using a numerical example based on the SOI platform. We assume the center wavelength to be  $1.55 \mu\text{m}$  and the refractive indices for Si and  $\text{SiO}_2$  are  $n_{\text{Si}} = 3.476$  and  $n_{\text{SiO}_2} = 1.5$ , respectively. We assume the spacing between the output of neighboring waveguides to be  $3 \mu\text{m}$ , the diffraction angle  $\theta_{\text{diff}} = 0^\circ$  at the center wavelength, and the length of the FPR to be  $R_{\text{FPR}} = 1.5 \text{ mm}$ .

Figure 2 shows the calculated transverse dispersion at the focal plane of the output FPR of a slow-light AWG as a function of the group index  $n_{g,\text{wg}}$ . Here the transverse dispersion is  $dx/d\lambda = R_{\text{FPR}}d\theta_{\text{diff},m}/d\lambda$ , where the

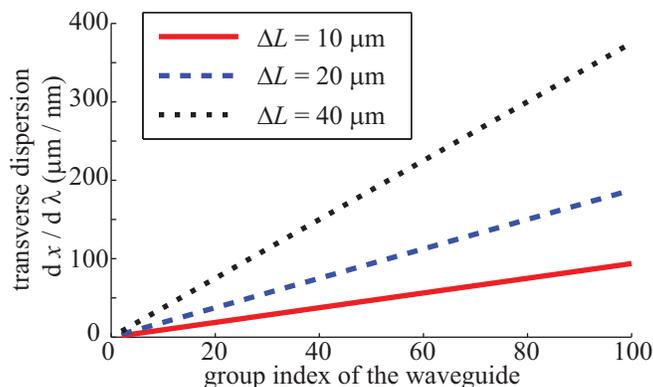


Figure 2. Linear transverse dispersion at the focal plane of the output FPR as a function of the group index of the waveguide of a slow-light AWG with  $\Delta l = 10, 20$  and  $40 \mu\text{m}$ , respectively.

angular dispersion  $d\theta_{\text{diff},m}/d\lambda$  is given by Eq. 3. When  $n_{g,\text{wg}} = 3$  and  $\Delta L = 10 \mu\text{m}$ , the transverse dispersion is approximately  $2.8 \mu\text{m}/\text{nm}$ , which is just adequate to separate two wavelengths differing  $1 \text{ nm}$  as two spectral channels in a wavelength division multiplexing system. When  $n_{g,\text{wg}} = 100$ , the transverse dispersion increases to  $94 \mu\text{m}/\text{nm}$ . If we let  $\Delta L = 40 \mu\text{m}$ , the transverse dispersion is  $375 \mu\text{m}/\text{nm}$ . If the distance between neighboring output waveguide is  $3 \mu\text{m}$ , this indicates a spectral resolution of  $1 \text{ GHz}$ . Note that the group index in photonic crystal waveguides can be as large as  $230^{22,23}$  or even more, which indicates the possibility of a further increase in the spectral resolution.

### 3. DESIGN AND FABRICATION OF A FLAT-BAND SLOW-LIGHT WAVEGUIDE

An on-chip slow-light medium that is suitable for spectroscopic applications has to meet a number of criteria,<sup>24</sup> including a large wavelength range over which the group index maintains approximately constant, and a large ratio between the group index and associated loss.

Two dimensional (2-D) photonic crystal (PhC) structures offer a very promising approach for generating on-chip slow light. In particular, line defect PhC waveguides realized on a SOI platform have been demonstrated to have very small group velocities below  $c/200$ .<sup>22,25,26</sup> The dispersion properties of such waveguides can be tailored<sup>27</sup> with the objective of achieving a low and constant value of the slope over a section of the dispersion curve, to produce the so-called flat-band slow light.<sup>28</sup> Such dispersion engineering can be realized in a line defect PhC waveguide, for example, by shifting the positions of the first two rows of holes closest to the line defect, in a direction perpendicular to the light propagation direction.<sup>27,28</sup> Our plan is to employ this as our first approach to designing the slow-light PhC waveguides for integrating in the slow-light spectrometer as shown in Figure 1. The fabrication of these PhC structures necessitates the use of electron beam lithography for obtaining extremely high precision (within  $2 \text{ nm}$ ) in the position and size of the holes, in order to achieve high group index.<sup>29</sup>

One dimensional (1-D) PhC structures such as photonic wires with a Bragg grating along the propagation direction<sup>30-33</sup> offer an alternate approach to designing slow-light waveguides, albeit with moderate group index compared to line defect PhC waveguides. Their main advantages lie in their ease of fabrication using standard techniques such as deep-UV photolithography and in their ease of on-chip integration. We explore two kinds of designs for wide band slow-light based on the modulation of the effective refractive index of the photonic wire using (i) periodic insertion of holes and (ii) by introducing corrugations in the side walls of the photonic wire.

#### 3.1 Photonic wires with periodic holes

Figure 3 shows the structure of the 1-D grating waveguide of width  $w_i$ , and periodically spaced holes inside the silicon layer of  $220 \text{ nm}$  thickness. The bottom silica ( $\text{SiO}_2$ ) cladding layer is  $2 \text{ micron}$  thick. The holes, also filled with silica, have a radius of  $r$ . They are spaced apart with a lattice constant of  $a$  along the  $x$  axis as shown in Figure 3. The dispersion curves for this structure are calculated using three dimensional (3-D) plane wave expansion (PWE) method.<sup>34</sup> We focus on the second band for the symmetric TE-like guided mode propagating

in the waveguide. Our PWE simulations show that the band flatness close to the Brillouin zone can be controlled by increasing the diameter of the holes. Figure 4(a) shows the results for the edge of the dispersion bands for  $a = 456$  nm,  $r = 115$  nm and  $w_i = 490$  nm for light transmitted at  $\lambda = 1550$  nm. The lattice constant is varied in order to adjust the position of the flat second band in the desired wavelength range. The group index as a function of wavelength corresponding to the second band in Figure 4(a) is shown in Figure 4(b). It can be seen that a constant group index of about 8.5 for a bandwidth of 14 nm around 1550 nm. Further work is being carried out to increase the value of the constant group index and to determine the propagation loss due to scattering and out-of-plane radiation in this structure.<sup>29</sup> We are exploring various designs for coupling light into and out of the photonic wire waveguide with holes.

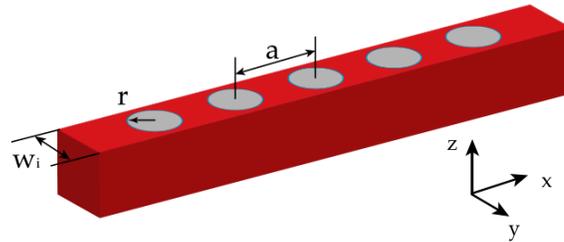


Figure 3. Two-dimensional schematics of a photonic wire waveguide with holes. The lattice constant is  $a$  and the hole radius is  $r$  while the width of the waveguide is  $w_i$ .

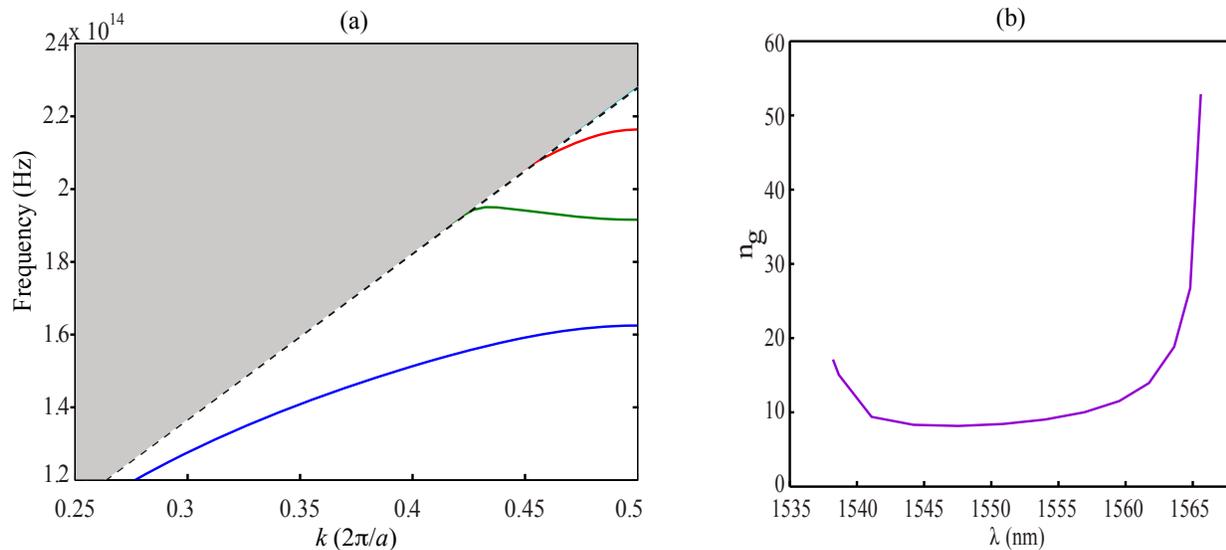


Figure 4. (a) Band diagram for a photonic wire waveguide with holes obtained with  $a = 456$  nm,  $r = 115$  nm and  $w_i = 490$  nm for light transmitted at 1550 nm. (b) Variation of group index over wavelength for the second band in Figure 4(a) in a region around 1550 nm.

### 3.2 Photonic wires with corrugated side walls

The schematic of the structure is shown in Figure 5. The dispersion bands calculated using 3-D PWE analysis for a waveguide with  $a=350$  nm,  $d=150$  nm,  $w_i=150$  nm, and  $w=850$  nm, are shown in Figure 6. We find that the length,  $w$  and width,  $d$  of the corrugations are key parameters that influence the flatness of the symmetric third band in Figure 6. The group index as a function of wavelength corresponding to the second band in Figure 6(a) can have values higher than 30 near the band edge, as shown in Figure 6(b). Our current work aims at optimizing the structural parameters in order to achieve wideband slow light corresponding to the third band

in the desired wavelength range of operation at 1550 nm. Ongoing work also involves designing an appropriate coupling section on either side of the slow-light waveguide for achieving minimum insertion loss. The final designs of the waveguides will be fabricated using deep-UV photolithography at IMEC, Belgium. The fabricated samples will be characterized using a standard insertion loss measurement setup and an optical dispersion measurement setup that is based on Fourier transform spectral interferometry.<sup>35</sup>

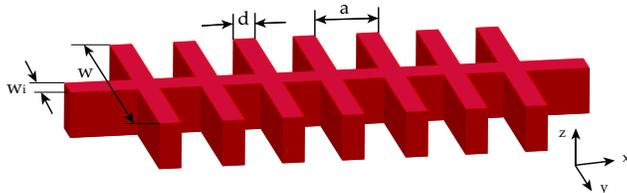


Figure 5. Two-dimensional schematics of a photonic wire with corrugations in the side wall. The length and width of the corrugation is  $w$  and  $d$ , respectively while the lattice constant is  $a$  and the width of the photonic wire is  $w_i$ .

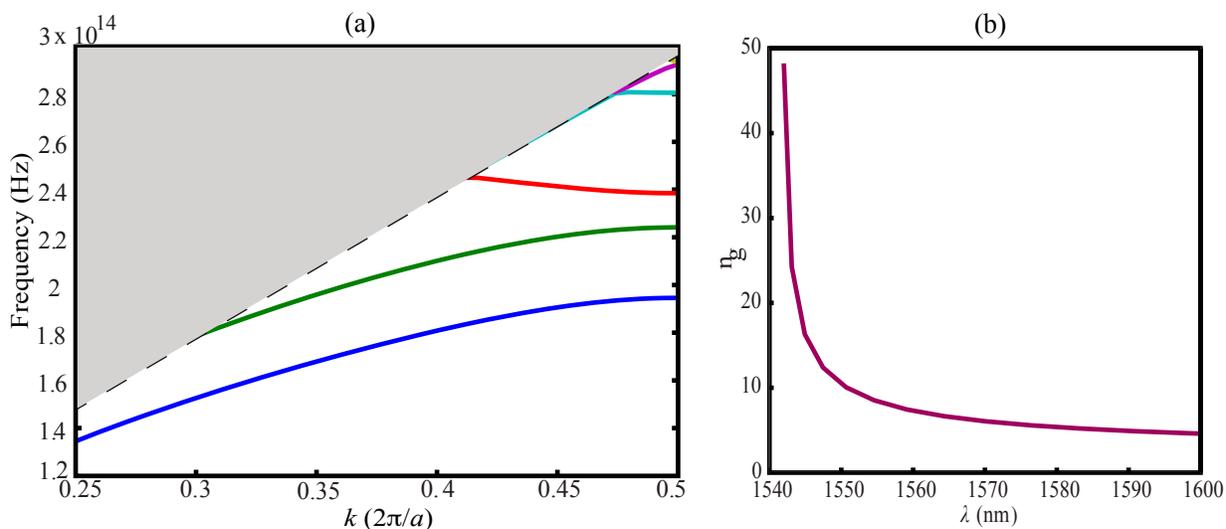


Figure 6. (a) Band diagram for a photonic wire waveguide with corrugations obtained with  $a=350$  nm,  $d=150$  nm,  $w_i=150$  nm, and  $w=850$  nm for light transmitted at 1550 nm. (b) Variation of group index over wavelength for the second band in Figure 6(a) in a region around 1550 nm.

#### 4. SUMMARY

We have described our development efforts involving on-chip spectroscopic interferometers using slow-light. By replacing regions of the ridge waveguides in an AWG spectrometer by slow-light waveguides, we have shown that the spectral resolution can be increased by a factor proportional to the ratio of the group index to the effective index of the slow-light waveguide. Our numerical simulation shows that spectral resolution of the order of GHz, essential for biological and chemical fingerprinting, can be achieved with this approach. We have explored slow-light designs based on 1-D periodic Bragg structures for their relative simplicity in fabrication compared to 2-D PhC line defect waveguides. Ongoing work includes optimizing the designs for obtaining a large and constant group index over a maximum possible bandwidth, as well as for obtaining minimum propagation loss through the slow-light waveguides.

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