Photonic Bandgap Quasi-Crystals for Integrated WDM Devices

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ABSTRACT

A novel concept of Photonic Bandgap Quasi-Crystal (PBQC) as a platform for planar integrated WDM optical devices is proposed. The PBQC can be lithographically fabricated in a planar waveguide as a computer-generated two-dimensional hologram. In this approach the spectral selectivity of Bragg gratings, focusing properties of elliptical mirrors, superposition properties of thick holograms, photonic bandgaps of periodic structures, and flexibility of lithography on planar waveguides are combined. In distinction to conventional combination of independent planar Bragg gratings, in PBQC we create multiple bandgaps by synthesizing a synergetic super-grating of a number of individual sub-gratings. The device spectral selectivity is determined by those of the sub-gratings. The super-grating comprises million(s) of dashes etched on an interface of a planar waveguide. Each dash is a binary feature placed by a computer program to serve simultaneously many channels. For realization of PBQC devices the software for generating super-gratings (GDS-II format) and 2-D simulation of its transfer function was developed. Direct e-beam writing and photolithography were used for manufacturing PBQC structures. For verification of the ideas behind the concept a number of multichannel MUX/DEMUX devices have been manufactured and experimentally tested. The results of detailed experimental study of 4- and 16-channel devices will be presented. Channel isolation ~30 dB was achieved in 4-channel devices. The applications of PBQC platform for integrated light wave circuits are discussed.

Key words: photonic bandgap quasi-crystal, planar demultiplexer, integrating element, hologram.

1. INTRODUCTION

Focusing and dispersive elements play an important role in lightwave integrated circuits used for WDM. The most known planar elements of this kind are AWGs[1,2]. Photonic bandgap crystal with lines of defects is an alternative promising approach to control light[3–5]. The use of quasi-periodic structures instead of periodic ones dramatically increases flexibility of design. To our best knowledge, we report for the first time MUX/DEMUX, based on PBQC platform, combining spectral selectivity of Bragg gratings[6,7], focusing properties of elliptical mirrors[7], superposition properties of thick holograms[8], photonic bandgaps of periodic structures, and flexibility of lithography on planar waveguides. In our approach all necessary bandgaps are created in a single synergetic super-grating. Typically, it comprises million(s) of dashes etched on an interface of a planar waveguide. Each dash is a binary structure placed by a computer program to serve simultaneously many channels that is why the term “synergetic super-grating” is used.

The potential of PBQC is not limited just by MUX/DEMUX application. This approach makes it possible to connect different points distributed over the light circuit platform by proper positioning of the corresponding supergratings at the planar surface. In distinction to the conventional ridge waveguide connectors, PBQC allows multiple intersections of optical passes connecting the different points. Moreover, due to resonance nature of the light propagation in PBQC these connections can be made in a spectral-selective manner.

PBQC is a complex platform for integrated optical devices. Several theoretical models should be used to understand its different properties.

Consider, first, operation of a single-channel PBQC device[7]. An elliptical mirror connects the foci ideally. To make the mirror spectrally sensitive, we have to place many slightly reflecting mirrors separated by half wavelength like in thin film filters and Bragg gratings – see Fig. 1. In practice the reflection is achieved by the modulation of the effective refractive index of the planar waveguide. It is important to stress that even after multiple reflections the beam is focused on the same point.

The photonic bandgap concept is useful to explain the flat top of a transfer function. Light waves cannot propagate in the bandgap, therefore in ideal model all energy will be reflected to the second focus. The width Δw of the bandgap is proportional to the variation Δn of effective refractive index: $\Delta w / w = \Delta n / n$. Typically, $\Delta n / n \approx 10^{-3}$.

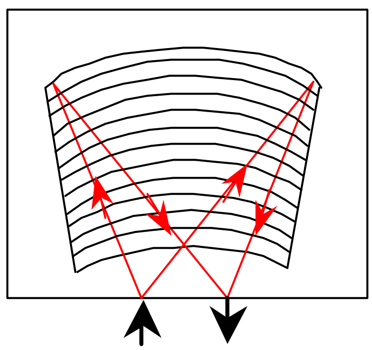


Fig. 1. Elliptical Bragg grating connects its two foci within the bandgap, corresponding to the given grating parameters.

Apodization (smoothing) of the grating input and output regions is a natural way to get steep rollout and good channel isolation. Theory of perturbation and Fourier analysis is the natural language for channel isolation. Our apodization is standard except smoothing is achieved by removing some lines from the grating.

Sequential positioning of multiple elliptical Bragg gratings with different bandgaps creates a multichannel device. However, this way does not look practical as the approach is not scalable to significant number of channels due to increased size and associated losses. In addition, each of these gratings will need its own apodization, increasing the total length even more.

Multiple elliptical Bragg gratings can be also made of dashed lines and overlaid as shown in Fig. 2. This superposition of gratings will need apodization only once in the beginning and once in the end of the pattern, decreasing the total length compared to stacked gratings. However, if we take into account that the dashes should not intersect to make the structure manufacturable with one-layer microlithography, it becomes clear that the total pattern length will be proportional to the number of channels N in the device.

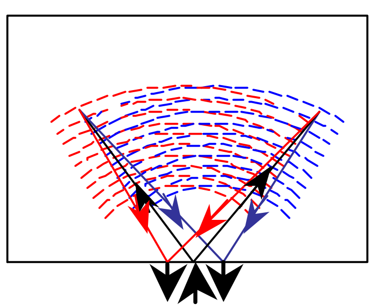


Fig. 2. Two overlaid dashed elliptical Bragg gratings.

A PBQC structure appears when we synthesize a super-grating of N sub-gratings so that each dash works for several channels simultaneously. Although the PBQC structure is not as regular as a photonic crystal, it's not random either. There is a long-range order in the PBQC determined by the interchannel spacing. PBQC structure is very flexible as it includes millions of almost identical small features and, by varying their positions, one can control integral parameters of the supergrating. An example of supergrating is shown in Fig. 3.

Finally, it should be pointed out that PBQC is a device with discrete dispersion. Namely, only those wavelengths appear at the well-determined stable outputs that reflect resonantly from the corresponding subgratings. All another wavelengths (outside the passband) will pass through. In this respect the PBQC dramatically differs from most other devices, say AWG or concave gratings, in which the dispersion is continuous thus seriously limiting the device performance. Within the passband of PBQC device the focal spot is virtually immobile. The stable positions of the output beams is the outstanding feature of PBQC allowing for designing devices with flat-top channel shape without penalty loss.

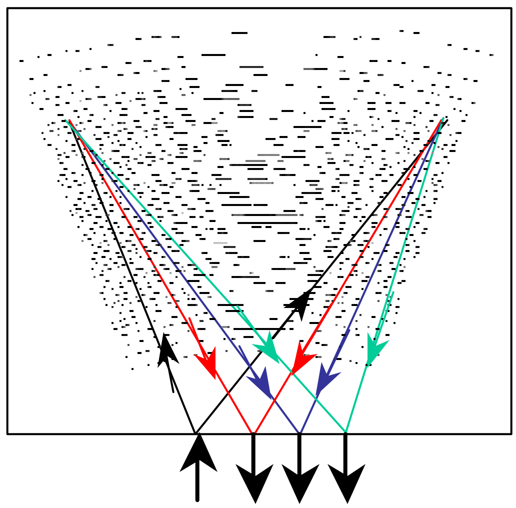


Fig. 3. Schematic example of supergrating (PBQC), synthesized of three subgratings

2. THEORY

In the first approximation the channels are independent, although, as we will see later, they can interfere. The possibility to overlay many images is well known in the theory of thick holograms. It can be shown that the transition from a sub-grating for one channel to an N-channel super-grating synthesized of N sub-gratings increases the integral bandwidth proportionally to $\sqrt{N}$. Indeed, let us compare a periodic structure with a quasi-periodic one with N periods made by rearrangement of the same dashes. It is known from the theory of Fourier transform that average amplitude of Fourier harmonics will be $f_k^2 \propto N^{-1}$, therefore the integral bandwidth $\sum_N \Delta w_i \approx N f_k \propto \sqrt{N}$. This increase in the integral bandwidth significantly relaxes many limitations on performance of PBQCs.

Polarization dependent loss (PDL), originating from differences in parameters of propagation and reflection in a planar waveguide for TE and TM modes, may be decreased or even eliminated by designing a planar with difference in effective refraction indexes for TE and TM modes exceeding the operation frequency range (about 2%). This provides the possibility of writing separate sub-gratings for each polarization (two sub-gratings per channel). Additional reflections lie outside the deployed bandwidth.

PBQC's binary structure makes mixing of channels a strongly nonlinear operation leading to harmonics generation. These undesirable harmonics lead to parasitic reflections and, consequently, to crosstalk. The most dangerous combination of sub-grating wave vectors is $\vec{k}_1 + \vec{k}_2 - \vec{k}_3$, which is close to main period of the grating. Having millions of dashes and a number of tuning parameters one can suppress several dozens of undesirable reflections, as it will be shown in sections Simulations and Experiment. This part of the theory is the most complex.

3. SIMULATIONS

Although the PBQC approach allows for numerous application in Integrated Lightwave Circuits (ILC), in this work we concentrated on multichannel MUX/DEMAX devices in order to verify the main ideas behind the concept of PBQC.
For designing and simulation of the PBQC devices a special software OptiMUX has been developed. Currently, it works mostly for MUX/DEMUX applications and includes five modules:

1. Waveguide Mode Analysis,
2. Grating Design,
3. Spectrum Simulation and Grating Generation,
4. Chip Design,
5. Database.

OptiMUX can analyze the multiplayer planar waveguides with the ability to design and simulate the complicated super-gratings located on upper and/or lower surfaces of a waveguide core. Sequential positioning of super-gratings (similar to Ref.7) is also possible as well as the custom-made apodization and chirp of the grating being designed.

As output, the software produces a GDS-II file for production and a 2-D simulation of the transfer function for the device being designed. All results are stored in the database together with experimental data received from characterization of fabricated devices.

Figure 4 shows the simulated transfer function of a four-channel PBQC demux with significant cross-talk between the channels. This is the influence of harmonics generated in the supergrating. By proper generation of super-grating, these harmonics can be reduced dramatically, as shown in Fig. 5.

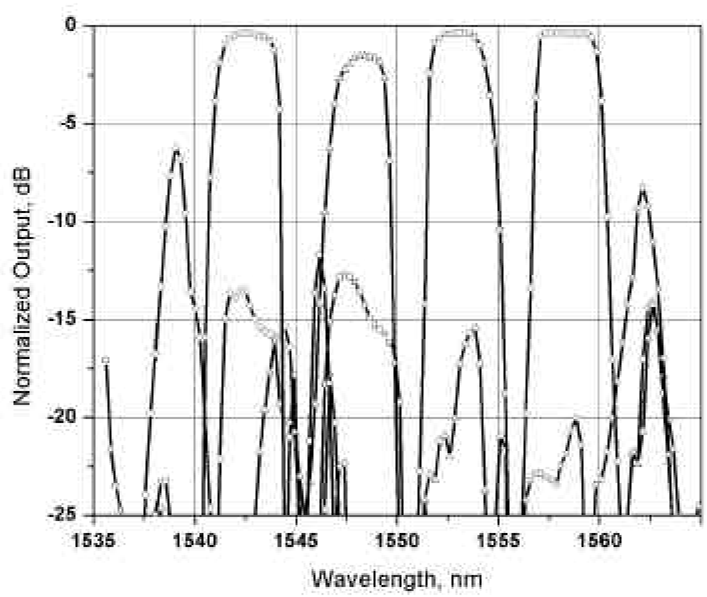


Fig. 4. Simulation of PBQC demux with significant cross-talk.

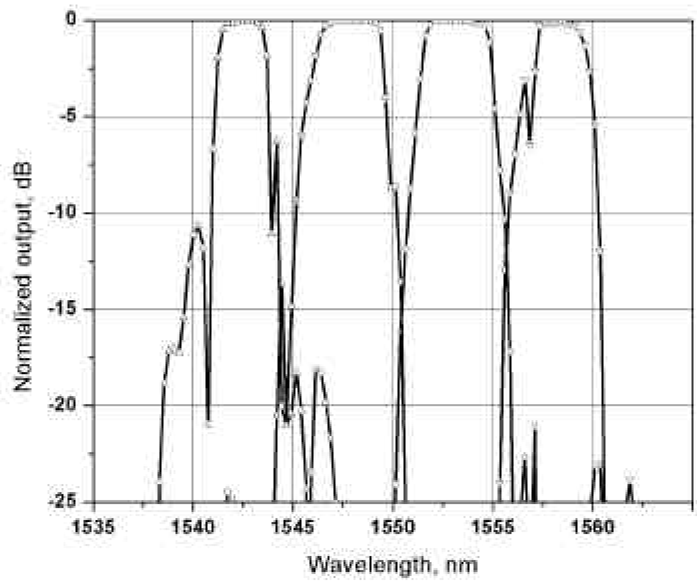


Fig. 5. Simulation of PBQC demux with reduced cross-talk.

Similar to photonic crystals, PBQCs have significant polarization dependent loss (PDL). To minimize PDL, the PBQC can be designed with separate sub-gratings for TE and TM modes for each channel, both of which have the identical transfer function. The results of the simulation are shown in Fig. 6.

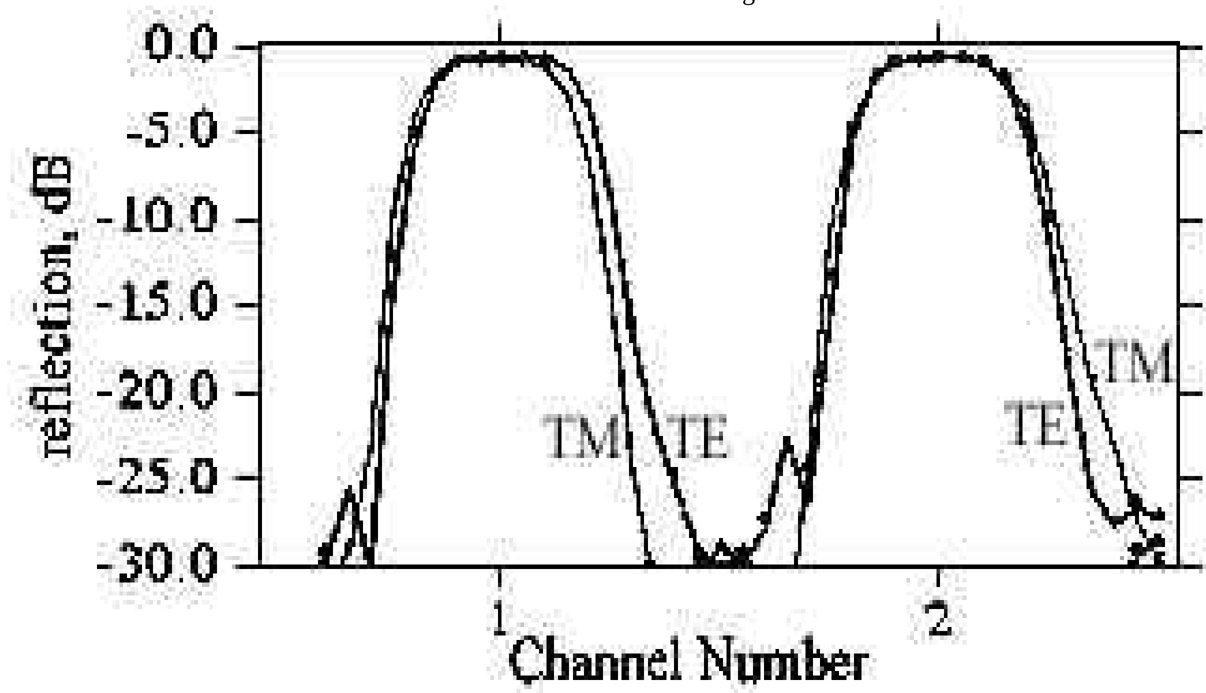


Fig.6. Two channels with minimized PDL (simulation).

Further improvement of the device parameters can be obtained by proper positioning the supergratings at the different sides of a waveguide core as it is illustrated in Fig. 7, where the results simulation of a 4-channel device are presented. Note the high simulation accuracy (~50 dB), and low cross-talk and high fill factor obtained in this simulation.

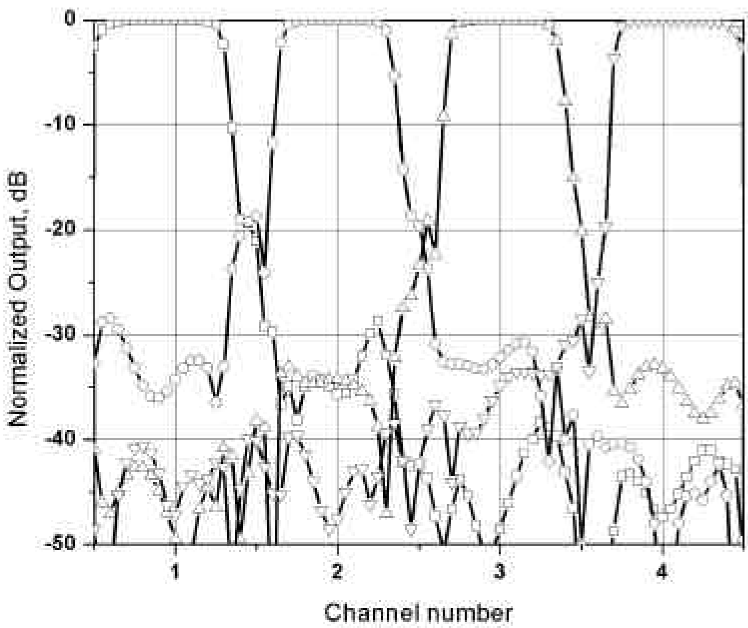


Fig. 7. Simulation of 4-channel PBCQ demux. Supergratings are disposed at both sides of the waveguide core. Spacing between channels equals 6.2 nm.

4. EXPERIMENTAL RESULTS

For fabrication of the PBQC structure on a planar the microelectronic technology was used. The planar substrate was a commercially available silicon wafer coated with SiO_2 / SiON / SiO_2 layers. A sketch of the device is shown in Fig. 8.

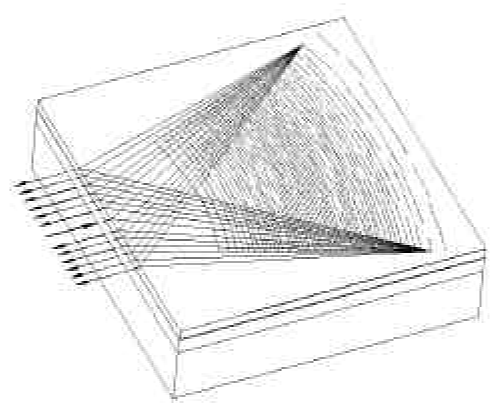


Fig. 8. Planar PBQC MUX/DEMUX.

Two fabrication processes have been developed based on electron-beam and photolithography. Electron-beam lithography was used for direct writing of a pattern. This technology allows for fast prototyping. An electron beam writer with variable-shape beam was employed to generate patterns. Most experiments have been performed with devices made using this technology. Fig. 9 shows an optical microphotograph of a PBQC device. We also used photolithographic technology to establish a process for low-cost, mass-manufacturing. The technology was proved to be successful and relatively simple as it is just a single-layer process. It is also compatible to the CMOS process, so can be reproduced in a standard way. In addition it is suitable for volume manufacturing.

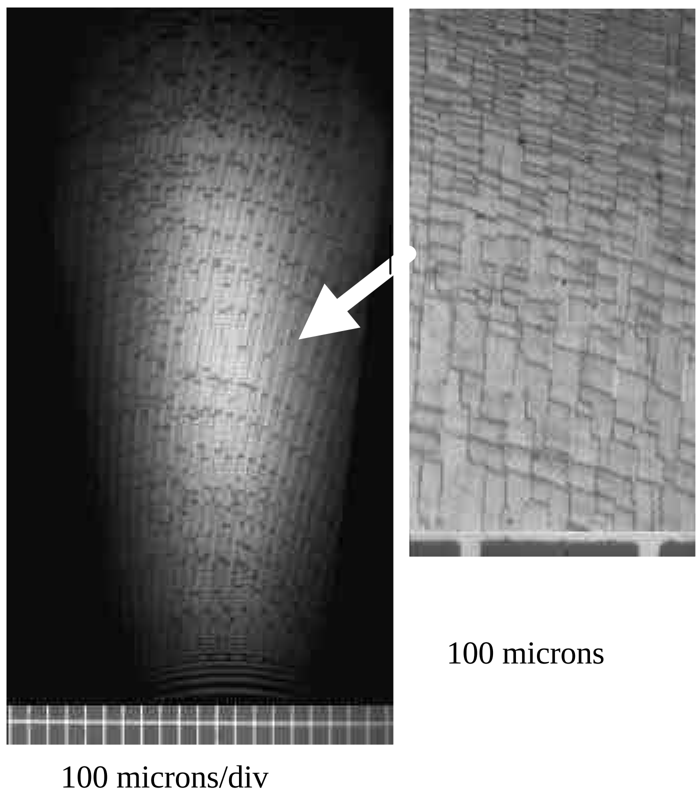


Fig.9. Optical micro photo of a 4-channel mux/demux based on PBQC technology.
Non-regularity is apparent, nonetheless there is a long-range order.

To study the PBQC performance and verify the ideas behind the concept most of fabricated devices undergo the detailed optical testing that includes microphotography and measurements of transfer function, scattering loss, and temperature drift.

In the measurements a semiconductor laser was used tunable in range of 1520-1580 nm. 10% of its output goes to a wavelength meter and 90% to a tested chip (DUT). Light is focused with a microobjective onto the edge of the chip, the FWHM of the focal spot being about 3.5 micrometer. The power of incident, transmitted, and back-reflected light is measured (with spatial resolution <5 micrometers) using an IR camera and/or digital power meters. Light distribution within the chip and side-scattered power (out of the chip surface) are recorded with a second IR camera. All instruments are computer-controlled. The testing setup optical scheme is presented in Fig. 10.

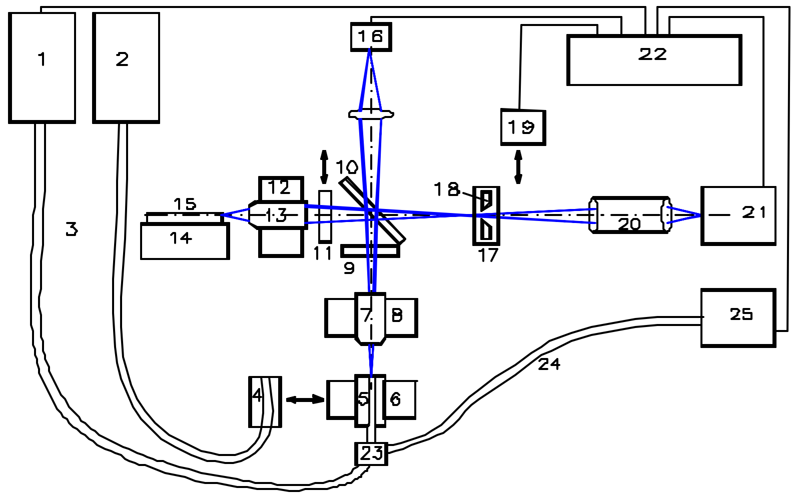


Fig.10 Testing setup optical scheme: 1 – Tunable IR Laser; 2 – He-Ne Laser; 3,24 – Single Mode Fibers; 4,5 – Fiber Holders; 6,8,12,14,17 – XYZ Stages; 7,13 – Microobjectives; 9 – Polarizer; 10 – Pellicle; 11 – Halfwave Plate; 15 – DUT; 16,19 – Power Meters; 18 – Iris Diaphragm; 20 – Relay Lens; 21 – IR Camera; 22 – PC; 23 – Coupler; 25 – Wavelength Meter.

Some results of testing are shown below in Fig. 11-16. Figures 11 and 12 show the transfer functions of four- and

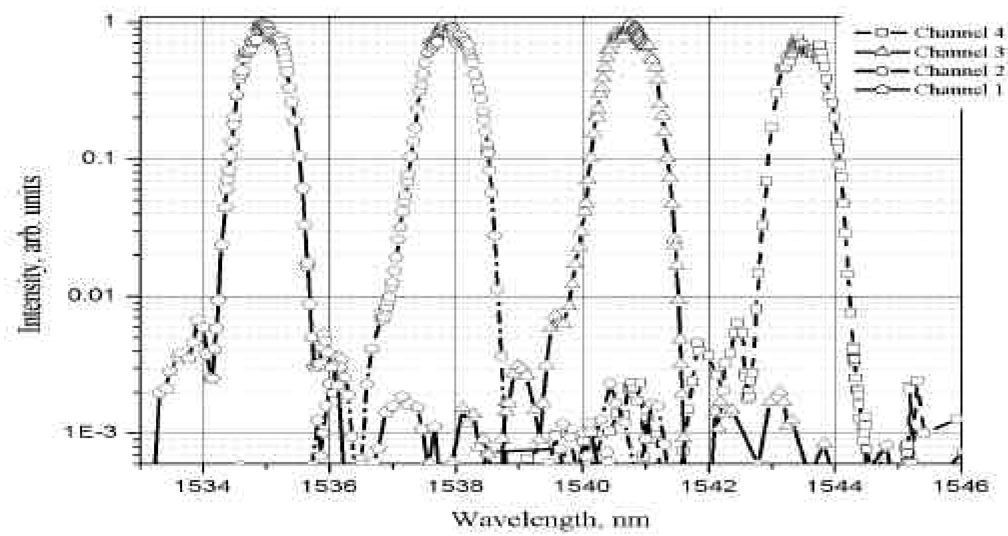


Fig. 11 Transfer functions of 4-channel devices.

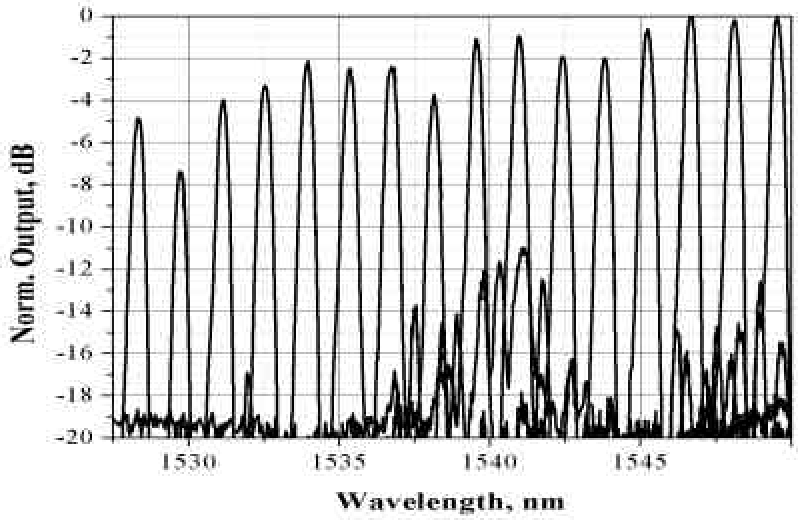


Fig. 12 Transfer functions of 4- and 16-channel devices.

sixteen-channel mux/demux devices, respectively. The four-channel mux/demux shows ~30 dB cross-talk and rather good shape of the channels. For comparison with simulations Fig. 13 shows in more detail the channel shape for the 4-channel device. Despite of the fact that the shape in Fig. 12 is quite symmetrical and clear within almost three orders of magnitude, the simulated shape as in Figs. 5,6 or 7 has yet to be obtained. The probable cause for this discrepancy is the high transmission loss. To verify this we have conducted reflection measurements with a set of similar gratings deposited at the same planar at the different distance from its input edge (each grating subtended the same solid angle). The absorption in the wafers used was found to be ~8 dB/cm. As our simulations show the absence of flat tops in our transfer functions can be accounted for by this high value of absorption. It should be also mentioned that the actual channel nonuniformity and crosstalk for the 16-channel device are lower than shown on the graph since some measurement artifacts contributed in it's values as we know now. Pigtailing should decrease those effects significantly.

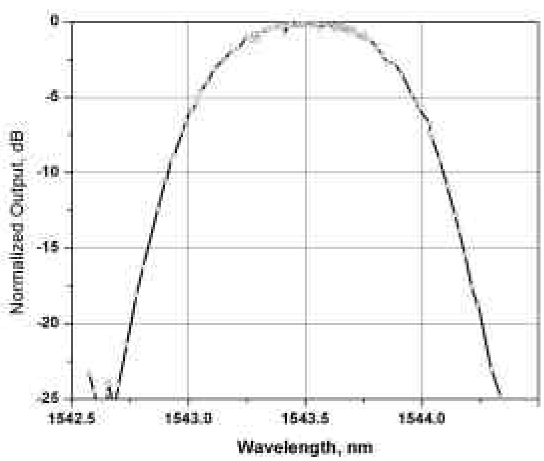


Fig.13. Four-channel device. Transfer function of one of the channels.

Figure 14 and 15 present the results of measuring a scattering loss in a four-channel device: some light scatters on the grating and escapes from the planar through its surface. As it can be seen on the plot in Fig. 14, the loss (bold line) in our device is measured to be below –19 dB, which is an insignificant value. To illustrate the effect of scattering Fig.13a,b shows the images of 4-channel PBQC MUX/DEMUX taken from the direction perpendicular to the planar surface. At the top of the figure one can see the input edge of the grating (the laser radiation input point is on top outside the frame border). In a) the laser wavelength is outside the passband. In this case the beam passes through the device and the radiation fills almost all grating length. On the contrary, in b) the laser wavelength lies within the passband, the backreflection is strong, and this happens at the very beginning of the grating as it is clearly seen in the figure. In fact, this method makes it possible to estimate the Bragg length of the grating.

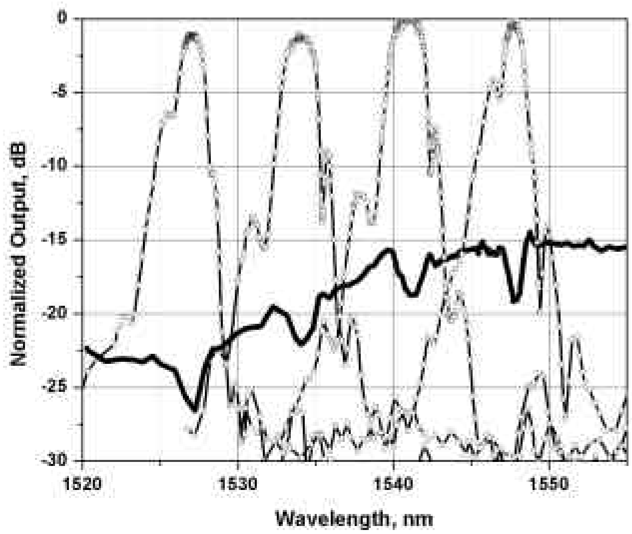
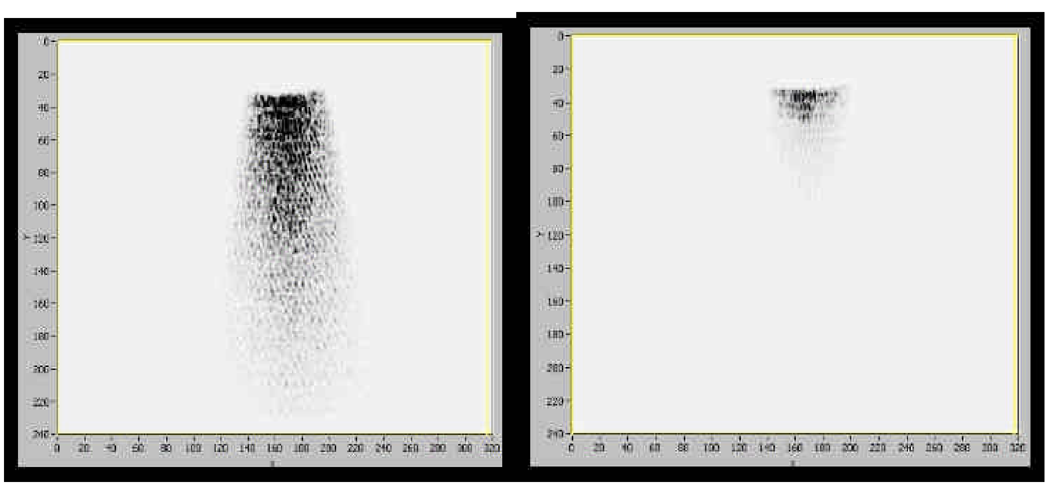


Fig. 14. Side scattering of light from a four-channel mux/demux.



a. b.

Fig. 15. Side-on images of 4-channel PBQC MUX/DEMAX surface: a) laser wavelength is outside the passband; b) laser wavelength lies within the passband. The full size of each frame is ~1.2*2.2 mm.

The temperature drift was also measured for a number of devices. It is found to be uniform for the all channels. The magnitude of drift is ~$1.5\cdot10^{-2}$ nm/^{0}C, as one can see from Fig.16.

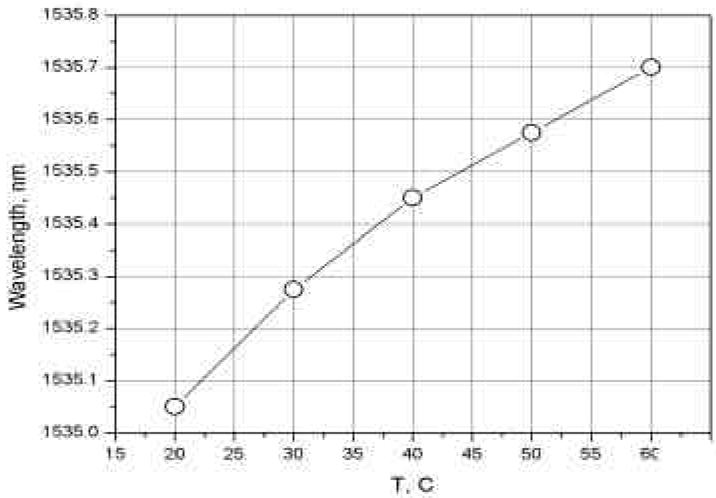


Fig.16. Temperature wavelength drift in 4-channel PBQC MUX/DEMUX.

5. CONCLUSIONS

We proposed, designed, developed, and tested a new technology for integrated optical devices, Photonic Bandgap Quasi-Crystals (PBQC). It combines spectrally selective properties of Bragg gratings, focusing properties of elliptical mirrors, superposition properties of thick holograms, photonic bandgaps of periodic structures, and flexibility of binary lithography on planar waveguides. A demonstration vehicle of PBQC is a flat-top planar mux/demux. By stopping the focal spot, a flat-top transfer function can be achieved without loss penalty. The special software, OptiMUX, for the design and 2-D simulation of PBQC devices was developed. PBQC MUX/DEMUX devices were fabricated by multiple methods. Electron beam lithography is used for prototyping. Feasibility of mass-fabrication using photolithography method has been established.

Experimental prototypes have been produced with up to 16 channels. Experimental data matches theory and simulation. The observed discrepancy can be accounted for by the high value of absorption in planar material. A scheme has been developed for PDL minimization in PBQC devices.

The Photonic Bandgap Quasi-Crystal technology is very promising and potentially disruptive to the PLC market, especially when used for connecting multiple active elements..

6. REFERENCES

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