Digital Planar Holography and Multiplexer/Demultiplexer with Discrete Dispersion

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ABSTRACT

Digital Planar Holography (DPH) has arrived due to progress in microlithography, planar waveguide fabrication, and theoretical physics. A computer-generated hologram can be written by microlithography means on the surface of a planar waveguide. DPH combines flexibility of digital holograms, superposition property of volume (thick) holograms, and convenience of microlithographic mass production. DPH is a powerful passive light processor, and could be used to connect multiple optical devices in planar lightwave circuits (PLCs), and if combined with active elements on the same chip, may perform not only analog operations but also logical ones. A DPH implementation of a multiplexer/demultiplexer with discrete dispersion is proposed and demonstrated, avoiding communication signal distortion inherent in multiplexers/demultiplexers with continuous dispersion. The concept of discrete dispersion leads to a device with a flat top transfer function without a loss penalty. The dispersion is created with custom-designed bandgaps for specific directions. A DPH hologram resembles a poly-crystal with long-range correlations, and it exhibits the properties of a quasi-crystal. Unlike photonic crystals, light in quasi-crystal may propagate in almost any direction. Single mode planar waveguides are specially designed to suppress parasitic reflections that appear due to mixture of TE-modes, TM-modes, and cladding modes. Demultiplexers with 2-32 channels were demonstrated on planar waveguides with binary single-layer lithography.

Key words: conventional planar hologram, digital planar hologram, volume hologram, planar lightwave circuit, photonic bandgap quasi-crystal, wavelength division multiplexer/demultiplexer, WDM, planar waveguide computer generated hologram, photonic crystal, inverse scattering.

1. INTRODUCTION to DIGITAL PLANAR HOLOGRAPHY

A hologram is a combination of millions of sub-wavelength size (a fraction of micron) features recorded in a transparent media. A hologram may mimic an image or even an optical device, and under certain conditions, such a hologram may be used in lieu of the original device. Analog holograms are made with conventional photographic materials, copying existing objects only. Digital holography is where a computer program generates positions of millions of holographic features and microlithography prints a hologram of an object that never physically existed. Until recently, digital holography was mostly limited to printing small images like logos, decorative foils, et cetera, and making optical devices was difficult due to limitations of conventional geometry. In that geometry, the light is directed under an angle to the hologram plane and travels in a hologram a very short pathway. To scatter light on micron scale the perturbations must be strong, thus leading to parasitic images, loss of light, and limited capacity to write many images on the same hologram[1]. The idea of the new planar geometry is to let light to travel inside hologram for thousands of wavelengths, as shown in Fig. 1, thus greatly increasing possibility for light processing. That approach was used for volume holographic memory, but at the time of this writing, digital volume holograms are technologically near impossible, since it is difficult to write an arbitrary image inside a volume media. Digital Planar Holography (DPH) combines the possibility to write

an arbitrary hologram with light traveling deep inside the hologram. One of the technological obstacles is the requirement for high quality blank planar waveguides; the wafers must have low attenuation, and be about a micron thick, and with a high degree of uniformity. The last condition is the most limiting, but requirements have been relaxed by the by optical industry to make arrayed waveguide gratings.
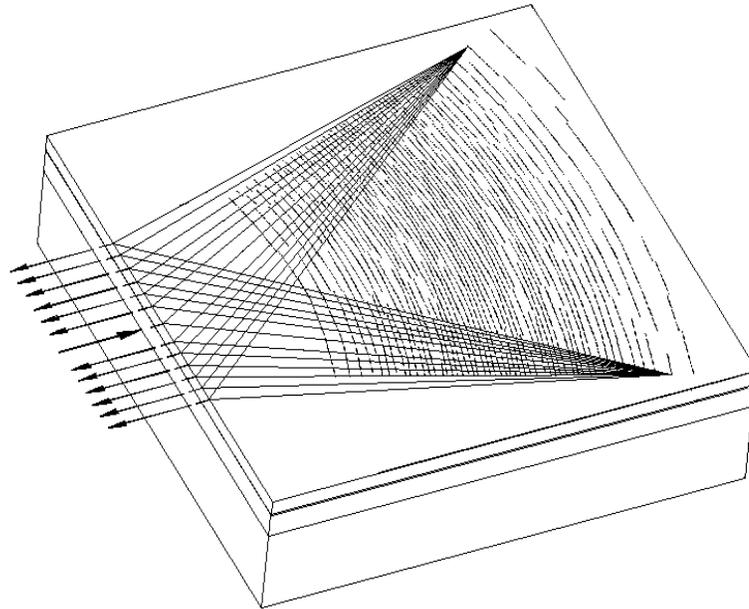

Fig. 1. Schematic illustration of DPH mux/demux PLC.

Below a brief comparison of digital planar holography (DPH) with the volume holography (VH) and the conventional digital holography (CDH) is presented.

1. Information capacity of DPH and CDH is approximately the same, since the writing media and the number of fringes are approximately the same, while the capacity of VH is much higher.
2. Variation of the (effective) refraction index is approximately the same for DPH and VH, and much smaller than for the variation of CDH. Thus DPH and VH allow superimposing many more images than CDH.
3. DPH and CDH could be made with microlithography and allow arbitrary fringe patterns, while VH is much more limited, since it is difficult to write deep inside solid materials.
4. The long light pathway inside DPH and VH holograms leads to high efficiency (nearly 100%) and the possibility to make devices with multiple reflections.
5. One important advantage CDH has over DPH and VH is that the optical paths are largely in the air, CDH is less vulnerable to inhomogeneity of materials. DPH is especially vulnerable because the effective refraction index depends both on the material (like in VH) and on the thickness of planar waveguides.

In view of the above considerations and taking into account the designing and manufacturing problems associated with large capacity VH, it may concluded that DPH seems to be the most promising approach for designing a broad variety of planar optical devices suitable for applications in different fields, including: optical fiber communication, spectrally-selective environmental monitors, high-resolution spectroscopy etc. The flexibility of the DPH approach can be easily understood by taking into account that digital holography allows for deterministic placing of millions of features on a planar surface. Consequently, it has millions of fitting parameters, resulting in considerable design flexibility. For example, DPH makes it possible to design spectral devices with almost arbitrary dispersive properties, even those with so-called discrete dispersion, when only the pre-determined set of narrow spectral bands is transmitted through the

device (the effect of discrete dispersion will be discussed in more detail below). Simulation of MUX/DEMUX with discrete dispersion is presented in Fig. 2.
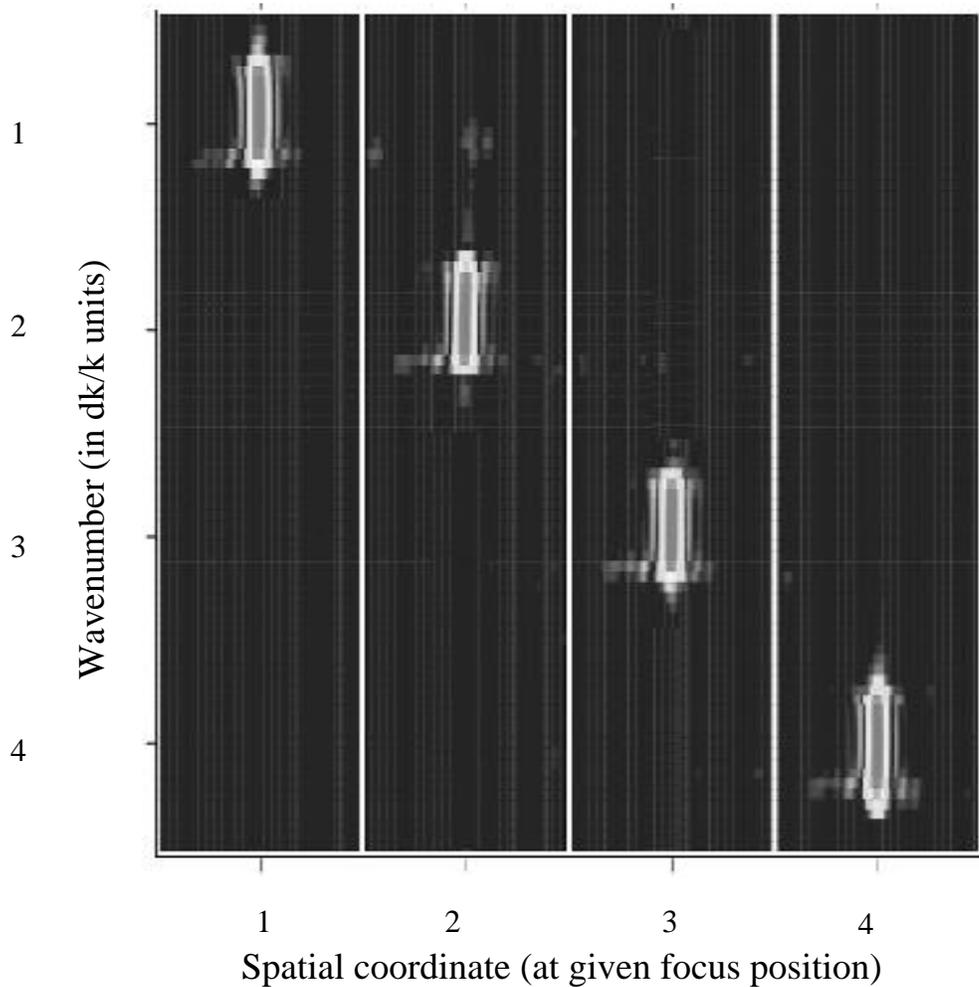

Fig. 2. Simulation of 4-channel device with discrete dispersion.

Modern micro-lithography allows fabrication of sub-wavelength patterns, so Digital Planar Holography has one thing left that it needs to succeed: what pattern should be written to make a desirable device. The approach is to characterize a device by Fourier components $f_{in}(x,y,\omega)$ and $f_{out}(x,y,\omega)$ of incoming and outgoing waves and then use these function to calculate the desirable holographic pattern. While real devices are 3-dimensional, use of a simplified model of a 2-dimensional Hamiltonian averaged over the third dimension should be satisfactory for many applications. Since the waves propagate freely in a blank waveguide, it is enough to write a model interaction Hamiltonian. Because the non-linear wave scattering is neglected, the Hamiltonian should be quadratic with respect to wave amplitude. It is also assumed that there is linearity with respect to variations of effective refraction index. Thus, the Hamiltonian has a form

$$H_{\text{int}} = \int f\ (x,y,\omega)\Delta n(x,y)f\ (x,y,\omega)d\omega$$

where $f(x,y,\omega)$ is the total wave function of specified frequency. Since all three functions under the integral are oscillating, the interaction is determined by resonances. It can be shown that to transform $f_{in}(x,y,\omega)$ into $f_{out}(x,y,\omega)$ the variation of effective refraction index (in arbitrary units) must be computed in the form

$$\Delta n(x,y) = \int f_{in}(x,y,\omega)f_{out}(x,y,\omega)d\omega$$

Some optimizations include correcting of the above formula for variation of $f_{in}(x,y,\omega)$ and $f_{out}(x,y,\omega)$ created by the hologram. To ease manufacturing, the function $\Delta n(x,y)$ should be substituted by binary (two-level) functions, preferably a composition of similar or identical elements of rectangular shape.

The photonic bandgap concept is useful to explain the flat top of a transfer function. Since light waves cannot propagate in the bandgap, then in ideal model all light will be reflected in some direction. The width $\Delta\omega$ of the bandgap is proportional to the variation Δn of effective refractive index of the corresponding Fourier harmonic. Typically, $\Delta\omega/\omega = \Delta n/n$, and inside bandgap, the amplitude of light decays exponentially with characteristic length L:

$$L = \lambda n / \Delta n \approx 10^3 - 10^4 \lambda.$$

The long length requirement is a main limitation of conventional holography, both digital and analog.

Since a DPH exhibits photonic bandgaps for some wave vectors, it may be treated as a photonic quasi-crystal. It is different from well-known photonic crystals both in physical appearance and structure of bandgaps. While a PDH has long-range order, it is not purely periodic. Photonic crystal bandgaps forbid propagation of light for nearly all directions except for a few specially designed lines of defects. A DPH bandgaps forbid propagation of light for a few specially designed arbitrary directions and frequencies. In a DPH light propagates freely, thus allowing easy interconnection of points in a planar waveguide. It is for this reason why it may serve as a good platform for integrated optical elements.

The commercially viable DPH should be binary because a binary relief is much easier to manufacture. Since a binarization is a strongly non-linear operation, binary DPH exhibits parasitic "ghost" images, which for a MUX/DEMUX are manifested as sources of channel crosstalk, which should be minimized.

The planar waveguides support several types of modes, known as core and cladding modes, each with two polarizations (TE and TM modes). Mixing of these modes creates additional ghost images. For example, a TE core mode may be reflected as a TE core mode or TE cladding mode. For example, if a hologram include the Fourier harmonic with wave vector $\vec{k}$, than the decay condition

$$\vec{k}_{in} = \vec{k} + \vec{k}_{out}$$

can be satisfied for output waves with the same wave vectors, but different frequencies. Since the difference in the effective refractive indices of the core and cladding modes is less than the difference in the refractive indices of the core and cladding materials, then the problem could be eased by making the waveguide of materials with high refractive index gradient, like Si on SiO_2. If the difference between the effective refraction indexes is small, then the ghost reflection will appear at a frequency shifted toward the red by $\Delta\omega/\omega = \Delta n/2n$.

While the transformation of TE-TM modes is weak, a hologram intended to process TE-TE also affects TM-TM processes. These problems are common for all planar devices, including non-holographic, and should be addressed during waveguide and device design, see, for example, MUX/DEMUX made by Henry et al[2].

Since DPH is very flexible and allows multiple reflections, many devices could be made, especially when combined with active elements. Perhaps, the most complex are the planar lightwave circuits, which may perform logical operations. Passive devices are simpler. MUX/DEMUX for optical fiber communications is the first demonstrated DPH device[8,9].

2. PDH MUX/DEMUX – GENERAL CONSIDERATIONS AND THEORY

Focusing and dispersive elements play an important role in lightwave integrated circuits used for WDM. The most well-known planar elements of this kind are AWGs[3,4]. Photonic bandgap crystal devices with lines of defects are an alternative, promising approach to control light[5,6]. The use of quasi-periodic structures instead of periodic ones dramatically increases flexibility of design. To the best of the authors' knowledge, it is reported for the first time[8,9] a MUX/DEMUX, based on DPH approach, combining spectral selectivity of Bragg gratings[7], focusing properties of

elliptical mirrors[2], superposition properties of thick holograms[1], photonic bandgaps of periodic structures[5,6], and flexibility of lithography on planar waveguides. In this approach all necessary bandgaps are created in a single synergetic super-grating. Typically, it is comprised of million(s) of dash-shaped pits etched onto an interface of a planar waveguide. Each dash-shaped pit is a binary structure placed by a computer program, and the perturbation it provides serves simultaneously many channels, hence the term "synergetic super-grating."

The potential of DPH is not limited just by MUX/DEMUX application, but this approach makes it possible to connect different points distributed over the PLC platform by proper positioning of the corresponding super-gratings on the PLC layout. In distinction to the conventional ridge waveguide connectors, in this case the multiple intersections of optical passes connecting the different points are possible. This fact is of great practical importance as it opens ways for designing and manufacturing complex optical circuits on a single planar platform with high fanin/fanout. Moreover, due to resonance nature of the light propagation in planar hologram, these connections can be made in a spectral-selective manner. DPH is a complex platform for integrated optical devices, and several theoretical disciplines should be used to understand the different aspects of DPH modeling and performance.

Consider, first, the operation of a single-channel device[2] that does not require holography. An elliptical mirror on a PLC connects the foci ideally. To make the device spectrally sensitive, many slightly reflecting mirrors are employed, separated by half wavelength like in thin film filters and Bragg gratings – see paper by Henry et al[2]. In practice the reflection is achieved by the periodic perturbation 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 MUX/DEMUX transfer function. Light waves cannot propagate in the bandgap, therefore in ideal model all energy will be reflected to the second focus. The width $\Delta\omega$ of the bandgap is proportional to the variation Δn of effective refractive index: $\Delta\omega/\omega = \Delta n/n$. Typically, $\Delta n/n \approx 10^{-3}$. Unlike photonic bandgap crystals, the light in a PBQC device may propagate in almost any direction, and by design, is prohibited a few directions. In contrast, photonic bandgap crystal device defects allows only a few directions of light to propagate.

Apodization (smoothing) of the grating input and output regions is a natural way to get steep rollout and good channel isolation. The theory of perturbation and Fourier analysis is the most suitable approach to treat the channel-isolation issues. The apodization is standard, except that 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 seem 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 would need its own apodization, increasing the total length even more.

Multiple elliptical Bragg gratings can be also made of segmented lines, which are overlaid. 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 it is taken into account that the dashes should not intersect to make the structure manufacturable with single-layer microlithography, it becomes clear that the total pattern length will be proportional to the number of channels N in the device.

A more sophisticated structure (referred to as a Photonic Band Gap Quasi-crystal – PBQC) appears when the software synthesizes a super-grating of N sub-gratings such that each dash contributes to several channels simultaneously. Although this structure is not as regular as a photonic crystal, it is not wholly random either. There is a long-range order in this DPH determined by the interchannel spacing. Its structure is very flexible as it includes millions of almost identical small features and, by varying their positions, the designer can control integral parameters of the supergrating.

Finally, it should be pointed out that the designed DPH is a device with discrete dispersion. Namely, only those wavelengths appear at well-determined output positions that resonantly sum the reflections from the corresponding sub-gratings. All another wavelengths (outside the passband) will transmit through the grating. In this respect the PBQC device dramatically differs from other devices, such as AWG or concave gratings which rely upon continuous dispersion. Within the passband of DPH the focal spot does not move as a function of wavelength and the stable output positions are

the outstanding feature of the PBQ approach, allowing for the design of MUX/DEMUX devices with flat-top channel shape without the loss penalty associated with most continuous-dispersion approaches.

In the first approximation the channels are independent, although, as it will be shown 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 for the average amplitude of Fourier harmonic the following condition is fulfilled: $f_k^2 \propto N^{-1}$. Therefore the integral bandwidth is

$$\sum_N \Delta \omega_i \approx N f_k \propto \sqrt{N} \ .$$

This increase in the integral bandwidth significantly relaxes many DPH performance limitations.

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 design bandwidth.

DPH's binary structure makes mixing of channels a strongly nonlinear operation, leading to generation of spatial harmonics. 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 permits the suppression of several dozens of undesirable reflections by proper hologram designing, as it will be shown in the next section. The non-linear optimization process is the most challenging part of DPH theory.

3. SIMULATIONS

Although the DPH allows for numerous application in PLCs, in this work development concentrated on multichannel MUX/DEMUX devices in order to verify the main ideas behind the concept of DPH. For designing and simulation of the DPH devices a special software suite called 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 in a CAD environment the complicated super-gratings located on upper and/or lower surfaces of a waveguide core. In essence, OptiMUX permits for the first time the solution and optimization of the inverse scattering problem for DPH photonic bandgap and PBQC devices. Chip layout functions such as sequential positioning of super-gratings (similar to Ref.2) 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 that can be sent to an IC mask shop to generate a single photomask for production, and a 2-D simulation of the transfer function for the device. All results are stored in the database together with experimental data received from characterization of fabricated devices. Figure 3 shows the simulated transfer function of a four-channel DPH demultiplexer with significant crosstalk between the channels. This is the influence of harmonics generated in the super-grating. By proper optimization of the super-grating, these harmonics can be reduced dramatically, as shown in Fig. 4.
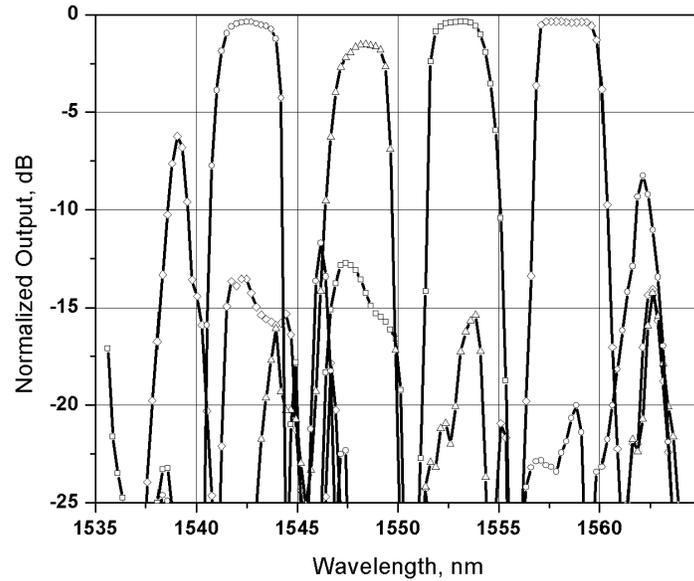
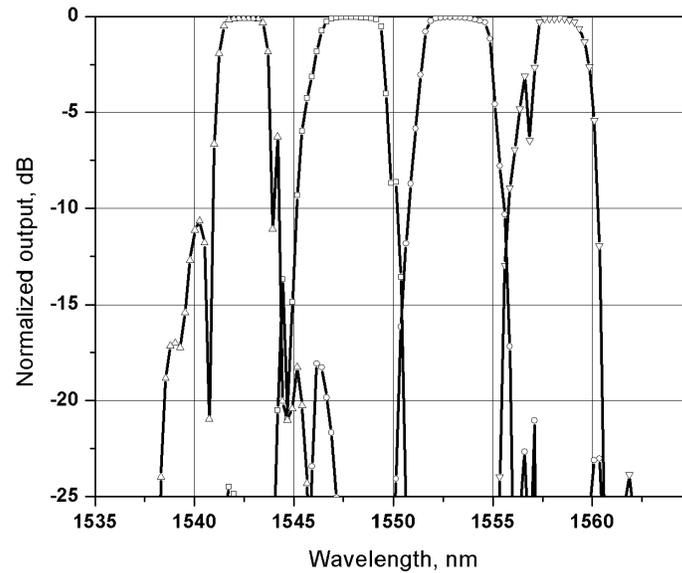Fig. 3. Simulation of PBQC demultiplexer with significant cross-talk.

Fig. 4. Simulation of optimized PBQC demultiplexer with reduced cross-talk.

Similar to photonic crystals, DPHs have significant polarization dependent loss (PDL). To minimize PDL, the DPH 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. 5.
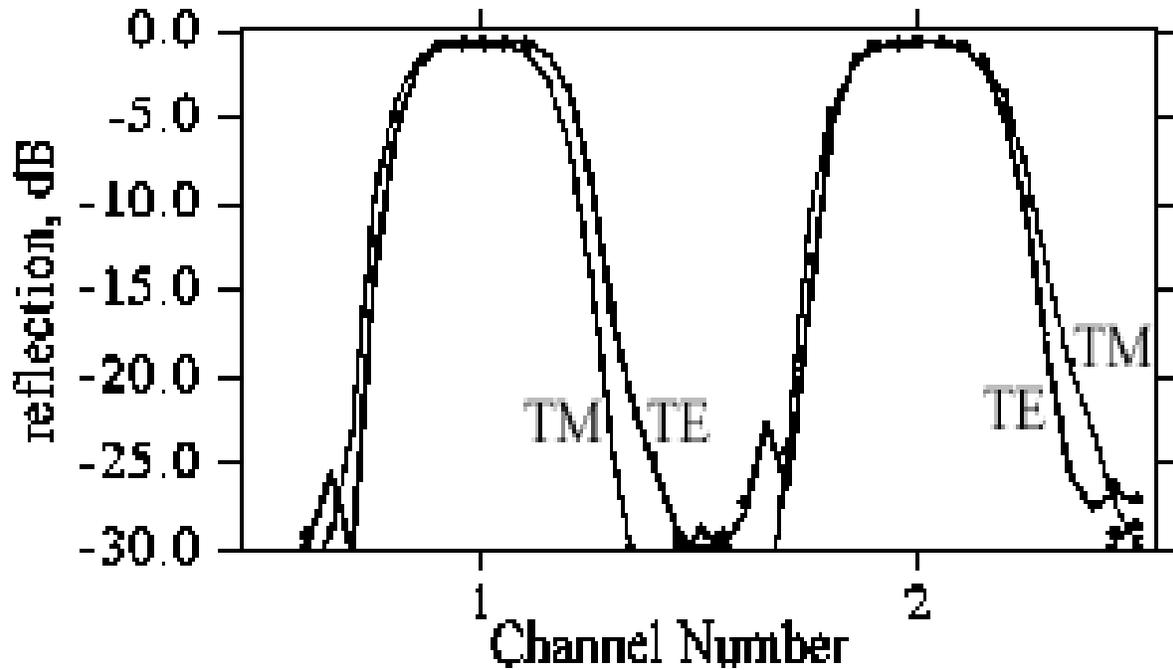
Fig.5. Simulation of two channel device with minimized PDL.

Further improvement of the device parameters can be obtained by proper positioning the supergratings at the different sides of a waveguide core, as illustrated in Fig. 6, where the results simulation of a 4-channel device are presented. Note the high simulation accuracy (~50 dB), low cross talk and high fill factor obtained in this simulation.
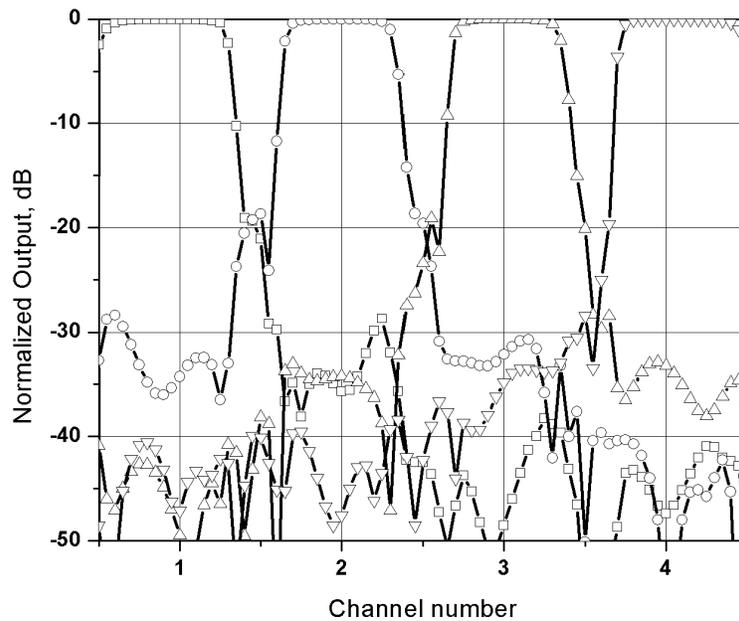

Fig. 6 Simulation of 4-channel PBCQ demultiplexer. Supergratings are disposed at both sides of the waveguide core. Spacing between channels equals 6.2 nm.
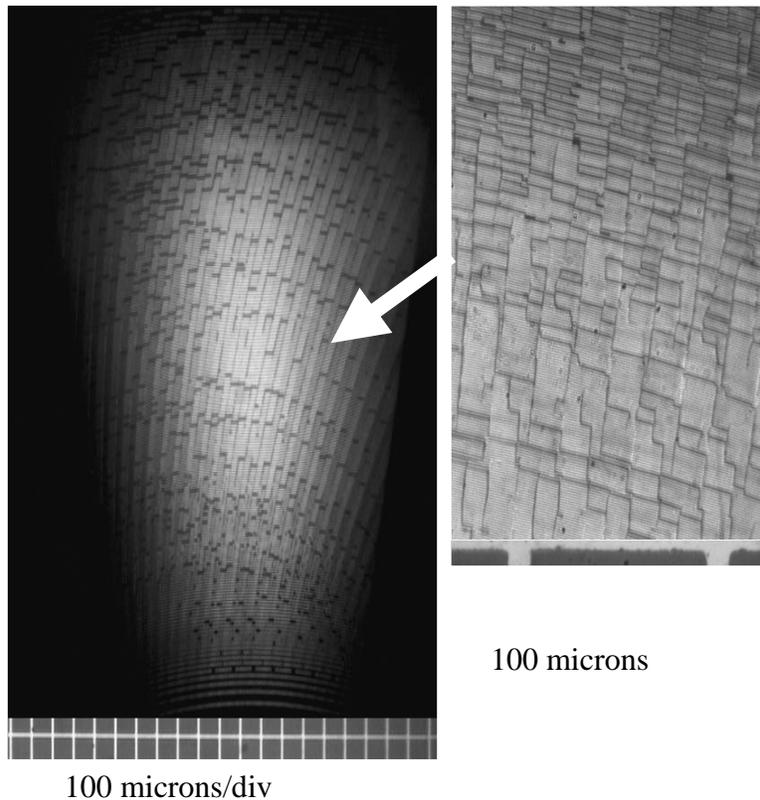
100 microns/div

100 microns

Fig.7. Optical micro photo of a 4-channel mux/demux based on PBQC technology.
Non-regularity is apparent, nonetheless there is a long-range order.

4. MANUFACTURING and TESTING of DPH MUX-DEMUX

For fabrication of the DPH structure on a planar waveguide, standard microelectronic processing was used. The planar substrate was a commercially available silicon wafer coated with SiO_2 / $SiON$ / SiO_2 layers. Two fabrication processes have been employed, based on either electron-beam or photolithographic technology. Electron-beam lithography was used for direct writing of a pattern for most of the experiments, which allows for fast prototyping. In this case, an electron beam writer with variable-shape beam was employed to generate patterns. Fig. 7 shows an optical microphotograph of a DPH device. Photolithographic technology was also used to establish a process for low-cost, mass-production. The technology was proved to be successful and relatively simple as it is just a single-step process. It is also compatible with standard CMOS processes, so can be reproduced in a low-cost manner in high volumes.

To study the DPH performance and verify the ideas behind the concept most of fabricated devices undergo the detailed optical testing that includes microphotography inspection, and measurements of transfer functions, scattering loss, and thermal stability.

In the measurements a semiconductor laser was used tunable in range of 1520-1580 nm. A fiber-optic coupler directs 10% of the laser output to a wavelength meter, and 90% through a polarizer towards the Device Under Test (DUT). Light is focused with a system of micro-objectives onto the edge of DUT chip, the FWHM of focal spot being about 3.5 microns. A zero order half-wave plate was used to control the polarization of the light at the device input, thus allowing for investigation of the device performance for TE- and TM-modes. The power of incident, transmitted, and back-reflected light can be measured (with spatial resolution < 3 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, and the optical testing setup is schematically illustrated in Fig. 8.
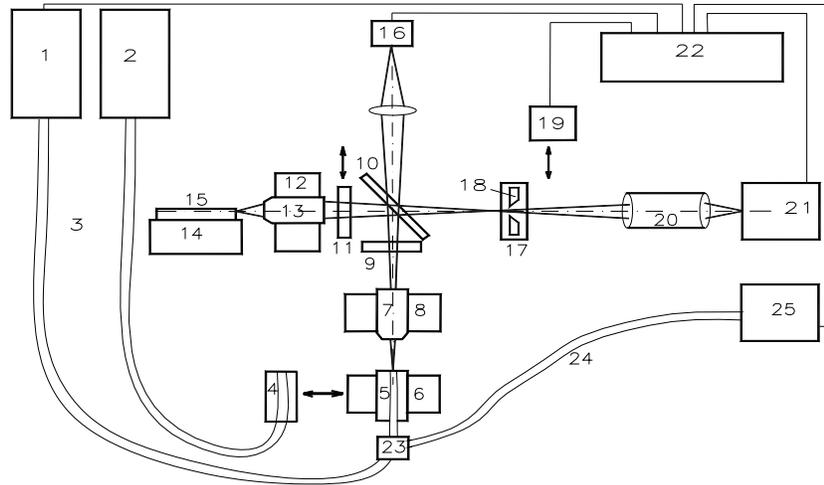
Fig. 8. Testing setup optical scheme: 1 - Tunable IR Laser, 2 - He-Ne Laser, 3, 24 - Single Mode Fibers, 4,5 - Fiber Holders, 6,8,12,14,17 – XYZ Stages, 7,13 – Microscope objectives, 9 – Polarizer , 10 – Pellicle, 11 - l/2 Wave Plate, 15 – DUT, 16,19 - Power Meters, 18 - Iris Diaphragm, 20 - Relay Lens, 21 - IR Camera, 22 – PC, 23 – Coupler, 25 - Wavelength Meter.

Some results of testing are shown below in Fig. 9-11. Figures 9 and 10 show the transfer functions of four- and sixteen-channel MUX/DEMUX devices, respectively. The four-channel MUX/DEMUX shows ~30 dB cross-talk and rather good shape of the passband. For comparison with simulations Fig. 11 shows in more detail the channel shape for the 4-channel device. Despite the fact that the shape in Fig. 11 is quite symmetrical and clear within almost three orders of magnitude, the simulated shape as in Figs. 4,5 or 6 has yet to be obtained. The probable cause for this discrepancy is the high transmission loss. To verify this, experiments have been conducted measuring the reflection with a set of similar gratings deposited on the same planar waveguide, at different distances from the input edge (each grating subtended the same solid angle). The absorption in the wafers used was found to be ~8 dB/cm. As simulations show, the absence of flat tops in the transfer functions can be accounted for by this high value of absorption. It should be also mentioned that the actual channel non-uniformity and crosstalk for the 16-channel device are lower than those shown on the graph due to measurement artifacts. Pigtailing should decrease those effects significantly, and allow significant further study of the PDH platform.
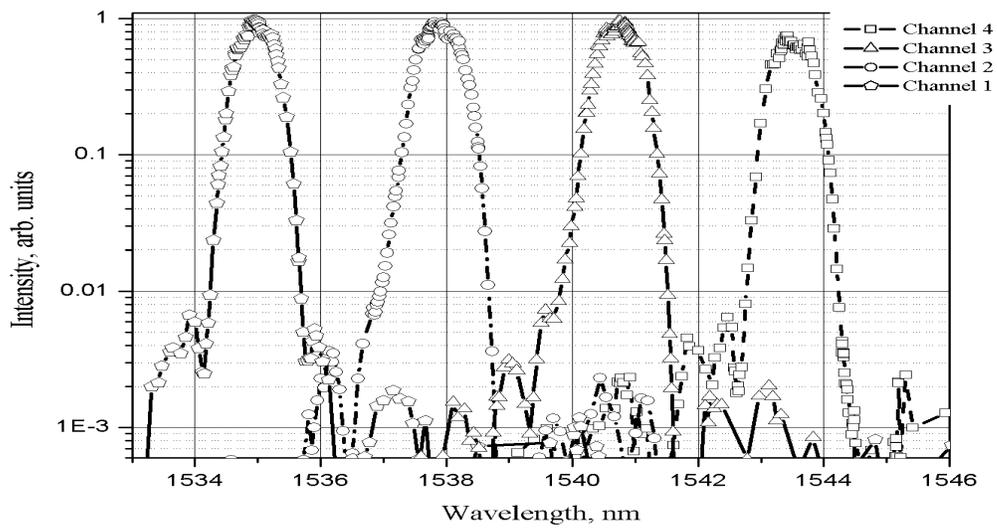
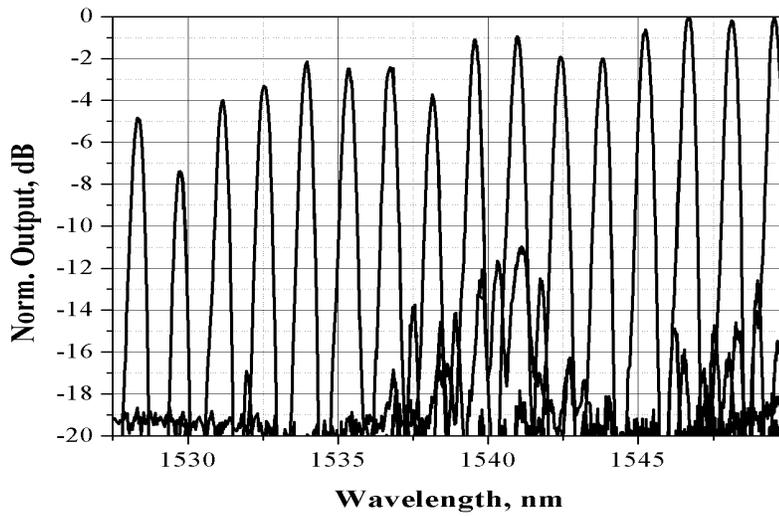Fig. 9. Measured transfer functions of 4- channel devices.

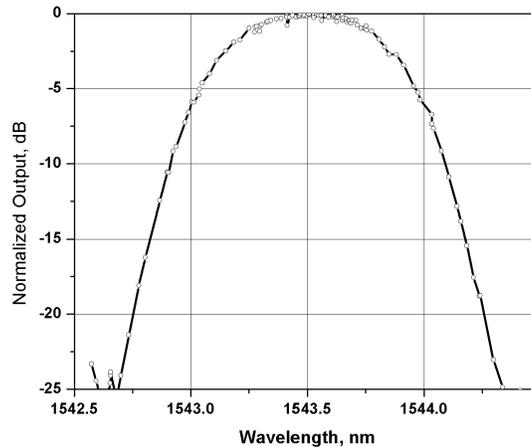Fig. 10. Measured transfer functions of 4- and 16-channel devices.

Fig.11. Four-channel device. Measured transfer function of one of the channels.

5. CONCLUSIONS

The possibilities of Digital Planar Holography (DPH) for designing complicated optical circuits on a single planar waveguide platform are considered. The new DPH technology for integrated optical devices is proposed, designed, developed, and tested. The demonstrated approach combines the 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. In a contrast to photonic crystals, the bandgaps of the planar hologram are very narrow and exists only for specially designed directions. The DPH approach is very flexible, and one device demonstrated is a flat top planar MUX/DEMUX device. By stopping the focal spot at the device output, a flat top transfer function can be achieved without a loss penalty. The special software, OptiMUX, for the design and 2-D simulation of DPH devices was developed. DPH MUX/DEMUX devices were fabricated by several methods, using standard processes. Electron beam lithography is used for prototyping, and the 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, except for a small discrepancy, which can be accounted for by the high value of absorption in planar material. A methodology has been developed for PDL minimization in DPH devices.

The technology based on Digital Planar Holography is very promising to the PLC industry (especially when used for connecting multiple active elements) as well as for a number of applications like material analysis, ultra-compact spectroscopy devices, high-resolution spectroscopy, etc.

REFERENCES

1. H. Kogelnik, "Coupled Wave Theory for Thick Hologram Gratings", The Bell System Technical Journal, **vol.48**, n.9, pp.2909 - 2947, November 1969.
2. C.H. Henry, R.F. Kazarinov, Y. Shani, R.C. Kistler, V. Pol, and K.J. Orlovsky, "Four-Channel Wavelength Division Multiplexer and Bandpass Filters Based on Elliptical Bragg Reflectors", Journal of Lightwave Technology", **vol. 8,** n.5, pp.748-755, May 1990.
3. M. K. Smit, "New focusing and dispersive planar component based on an optical phased array", *Electron. Lett.,* **vol. 24**, pp.385-386, 1988.
4. K. Okamoto, *"Fundamentals of Optical Waveguides"*, Academic Press, San Diego, CA, 2000.
5. E. Yablonovich, "Inhibited Spontaneous Emission in Solid-State Physics and Electronics", *Phys. Rev. Lett.*, **vol. 58**, pp.2059-2062, 1987.
6. J.D. Joannoupoulos, R. Meade, and J. Winn, *"Photon Crystals",* Princeton University Press, Princeton, NJ,

1995.

6.   R. Kashyap, *"Fiber Bragg Gratings"*, Academic Press, San Diego, CA, 2000.

8.   V. Yankov, S. Babin, I. Ivonin, A. Goltsov, A. Morozov, L. Polonskiy, M. Spector, A.Talapov, E.-B. Kley, H. Schmidt. "Multiwavelength Bragg Gratings and their Application to Optical MUX/DEMUX Devices*."* *Photonic Technology Lett*. **vol. 15**, pp. 410-412, 2003.

9.   V. Yankov, S. Babin, I. Ivonin, A. Goltsov, A. Morozov, L. Polonskiy, M. Spector, A.Talapov, E.-B. Kley, H. Schmidt, R. Dahlgren. Photonic Bandgap Quasi-Crystals for Integrated WDM Devices. Proc. SPIE, Vol. 4989, Photonics West, San Jose, 2003.