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. 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 microlithography mass production. DPH is the most powerful passive light processor conveniently placed on a chip. Planar digital hologram could be used to connect multiple optical devices in lightwave integrated circuits. If combined with active elements on the same chip, it may perform not only analog operations, but also logical ones. A DPH multiplexer/demultiplexer with discrete dispersion is proposed and made to avoid signal distortions inherent in multiplexers/demultiplexers with continuous dispersion. Discrete dispersion leads to a flat top transfer function without loss penalty. The dispersion is created with custom-designed bandgaps for a specific directions. Hologram resembles a poly-crystal with long-range correlations, and it exhibits the quasi-crystal properties. Despite photonic crystals, light in quasi-crystal may propagate in almost any direction. Single mode planar waveguides are specially designed to suppress ghost reflections which appear due to mixture of TE-modes, TM-modes, and cladding modes. Demultiplexers with 2-32 channels were made on the planars with a binary single layer lithography.

Key words: conventional planar hologram, digital planar hologram, volume hologram, light integrated circuit, photonic bandgap quasi-crystal, planar multiplexer/demultiplexer.

1. INTRODUCTION into DIGITAL PLANAR HOLOGRAPHY

A hologram is a combination of millions sub-wavelength (a fraction of micron) features recorded in a transparent media. Hologram may copy an image or even an optical device. After that, the hologram may be used instead of the device. Analog holograms were made with conventional photo-materials, coping existing objects only. Digital holography has arrived when microlithography moved to sub-micron features. Computer program generates positions of millions of holographic features and microlithography prints holograms of an object, which never existed. Until recently, digital holography was mostly limited to printing small pictures like logos etc. Making optical devices was difficult due to limitations of conventional geometry, below referred as a plane 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 ghost 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, see Fig. 1, thus greatly increasing possibility for light processing. That idea was used in the volume holographic memory, but digital volume holograms are technologically virtually impossible now since it is difficult to write an arbitrary image inside a volume media. Digital Planar Holography combines the possibility to write an arbitrary hologram with long light way inside the hologram. One of technological obstacle is the high quality requirements for blank planar waveguide. The waveguides must be about a micron thick, transparent and very uniform to transmit light without distortion. The last condition is the most limiting, but it was essentially eased by optical industry to make arrayed waveguide gratings.

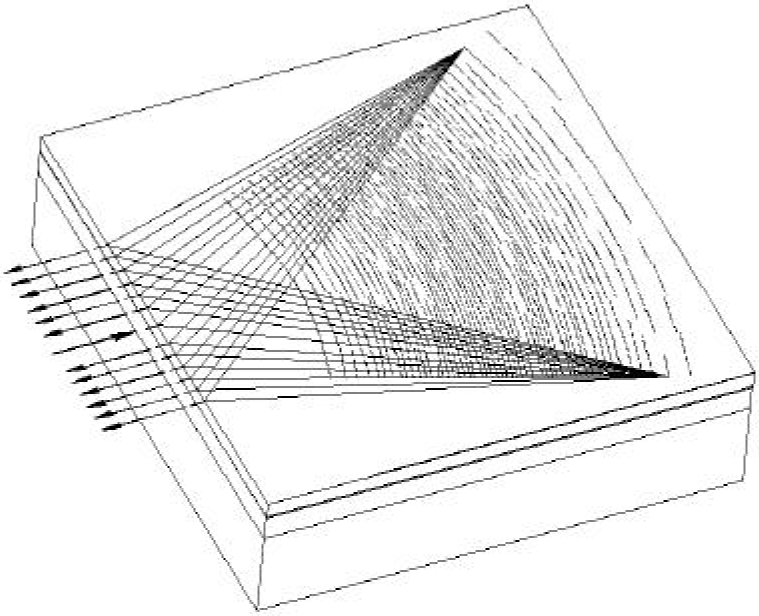

Fig. 1. Schematic example of DPH mux/demux.

Below the brief comparison of planar digital holography 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 the variation of the refraction index of CDH. Thus DPH and VH allow to superimpose much more images than CDH.
3. DPH and CDH could be made with the microlithography and allow arbitrary fringe patterns, while VH is much more limited since it is difficult to write inside solids materials.
4. The long light pathway inside DPH and VH holograms leads to nearly 100% reflection efficiency and possibility to make devices with multiple reflections.
5. CDH has important advantage over DPH and VH since the difference in the optical lengths is in the air, therefore it is not so vulnerable to inhomogeneity of materials. On the contrary, DPH is especially vulnerable because the effective refraction index depends both on 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, we may conclude 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, spectral-selective environment monitors, high-resolution spectroscopy etc. The flexibility of DPH approach can be easily understood if one takes into account that digital holography allows for arbitrary placing the million features on a planar surface. Consequently, it has millions fitting parameters, that, in its turn, results in the design flexibility. For example, DPH makes it possible to design spectral devises with almost arbitrary dispersive properties, even the those with so-

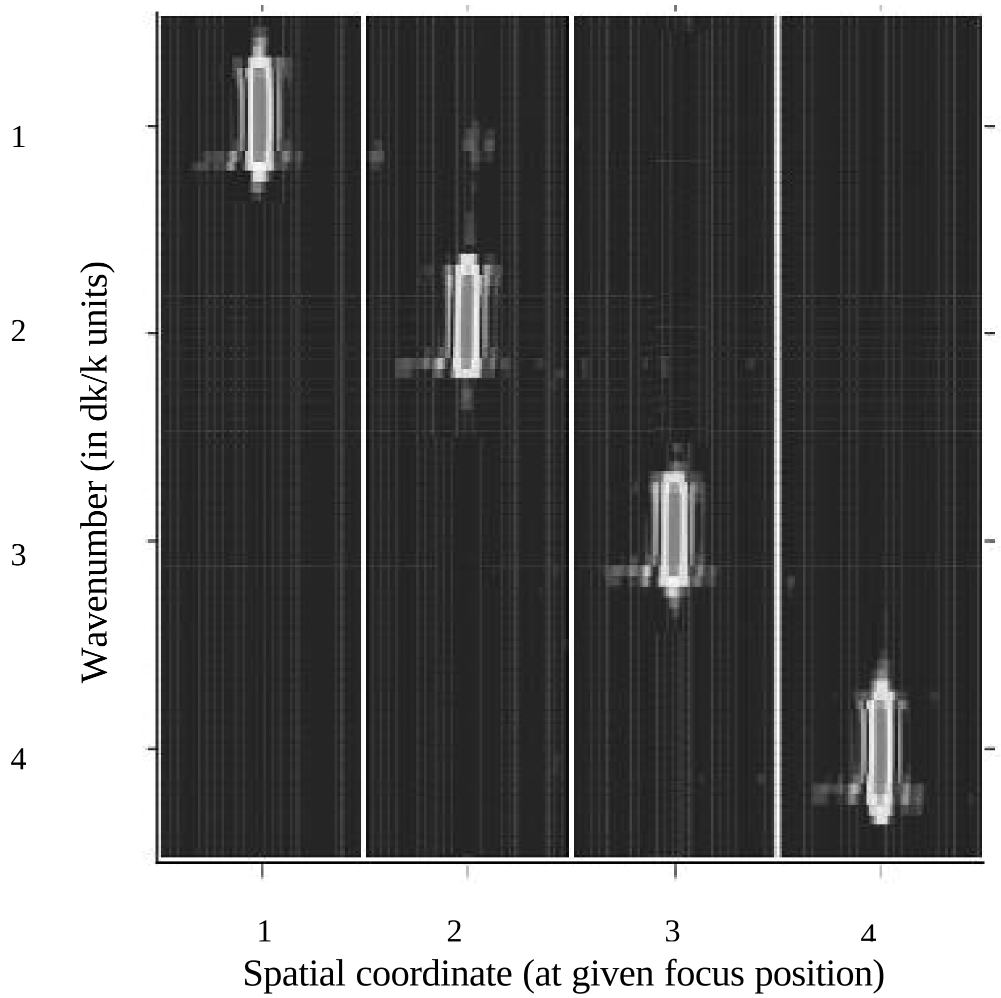

Fig. 2. Simulation of 4-channel device with discrete dispersion.

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 details below). Simulation of MUX/DEMUX with discrete dispersion is presented on Fig. 2. In devices like planar holographic spectrometers dispersion can be made almost arbitrary.

Modern micro-lithography allows fabrication of sub-wavelength patters, so Digital Planar Holography has one thing left that it needs to succeed: what pattern should be written to make a desirable device. Our approach is to characterize a device by Fourier components $f_{in}(x,y,\omega)$ and $f_{out}(x,y,\omega)$ of incoming and outcoming waves and then use these function to calculate the desirable holographic pattern. While real devices are 3-dimensional, using of a model 2-dimensional Hamiltonian averaged over the third dimension should be satisfactory for many applications. Since the waves propagate freely in a blank waveguide, its is enough to write a model interaction Hamiltonian. Because we neglect the non-linear wave scattering, the Hamiltonian should be quadratic with respect to wave amplitude. We also assume the 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 integral sign are oscillating, the interaction is determined by resonances. It may be shown that to transform $f_{in}(x,y,\omega)$ into $f_{out}(x,y,\omega)$ one has to create the variation of effective refraction index (in arbitrary units) in the form

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

Some variations 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. Light waves cannot propagate in the bandgap, therefore in ideal model all energy will be reflected in some direction. The width Δw of the bandgap is proportional to the variation Δn of effective refractive index of the corresponding Fourier harmonic. Typically, $\Delta w/w=\Delta n/n$. Inside bandgap the amplitude of light decays exponentially with characteristic length L:

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

This long length is the main reason dramatically limiting the possibilities of conventional plane holography, both digital and analog.

Since a planar digital hologram exhibits photonic bandagaps for some wave vectors, it may be treated as a photonic quasy-crystal. It is different from well known photonic crystals both in physical appearance and structure of bandagaps. While a planar digital hologram has long range order, it is nor periodical. Photonic crystal bandgaps forbid propagation of light for almost all directions except few specially designed lines of defects. A planar digital hologram bandagaps bandgaps forbid propagation of light for a few specially designed directions and frequencies. In a planar digital hologram lights propagates almost free, thus allowing easy interconnection of points in a planar waveguide. It is the reason why it may serve as a good integrating element.

A digital hologram should be binary because a binary relief is much easier to manufacture. Since a binarization is a strongly non-linear operation, binary DPH exhibits ghost images which should be minimized.

The planar waveguides support several types of modes, known as core and cladding modes, each with two polariations (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 out waves with the same wave vectors but different frequencies. Since the difference in the effective refraction indexes of the core and cladding modes is equal to the difference in the refraction indexes of the core and cladding materials or smaller, then the problem could be eased by making the waveguide of materials with high gradient of refraction index, like Si on SiO2. If the difference between the effective refraction indexes is small, then the ghost reflection will appear at a frequency shifted in the red direction $\Delta\omega/\omega=\Delta n/2n$.

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 integrated light circuits, which may perform logical operations. Passive devices are simpler. MUX/DEMUX for optical fiber communications is the first demonstrated DPH device[9,10].

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 known planar elements of this kind are AWGs[,3,4]. Photonic bandgap crystal with lines of defects is 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 our best knowledge, we reported for the first time[8,9] 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 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 DPH 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 super-gratings at the planar surface. 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 open ways for designing and manufacturing on the single planar platform the optical circuits of big complexity. 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. Several theoretical models should be used to understand the different aspects of DPH performance.

Consider, first, the operation of a single-channel device[2] which does not require holography. An elliptical mirror connects the foci ideally. To make the mirror spectrally sensitive, one has to place many slightly reflecting mirrors 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 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, $\Delta n / n \approx 10^{-3}$. Dislike photonic bandgap crystals, the light may propagate in almost any direction. One may say that photonic bandgap crystals direct light allowing only few directions of propagation while our quasi-crystals prohibit only few directions.

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 most suitable language to treat the channel-isolation issues. 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. 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.

A really sophisticated structure (sometimes it is called Photonic Band Gap Quasi-crystal – PBQC) appears when we synthesize a super-grating of N sub-gratings so that each dash works for several channels simultaneously. Although this structure is not as regular as a photonic crystal, it's not 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, one 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 the well-determined stable outputs that reflect resonantly from the corresponding sub-gratings. All another wavelengths (outside the passband) will pass through. In this respect the proposed device 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 DPH the focal spot at the output is virtually immobile. The stable positions of the output beams is the outstanding feature of proposed approach allowing for designing devices with flat-top channel shape without penalty loss.

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 for the average amplitude of Fourier harmonic the following condition is fulfilled: $f_k^2 \propto N^{-1}$. 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 DPH.

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.

DPH'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 by proper hologram designing, as it will be shown in sections Simulations and Experiment. This non-linear part of the DPH theory is the most complex.

3. SIMULATIONS

Although the Digital Planar Holography allows for numerous application in Integrated Lightwave Circuites (ILC), in this work we concentrated on multichannel MUX/DEMAX devices in order to verify the main ideas behind the concept of DPH.

For designing and simulation of the DPH 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.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 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 3 shows the simulated transfer function of a four-channel DPH demux with significant cross-talk between the channels. This is the influence of harmonics generated in the super-grating. By proper generation of super-grating, these harmonics can be reduced dramatically, as shown in Fig. 4.

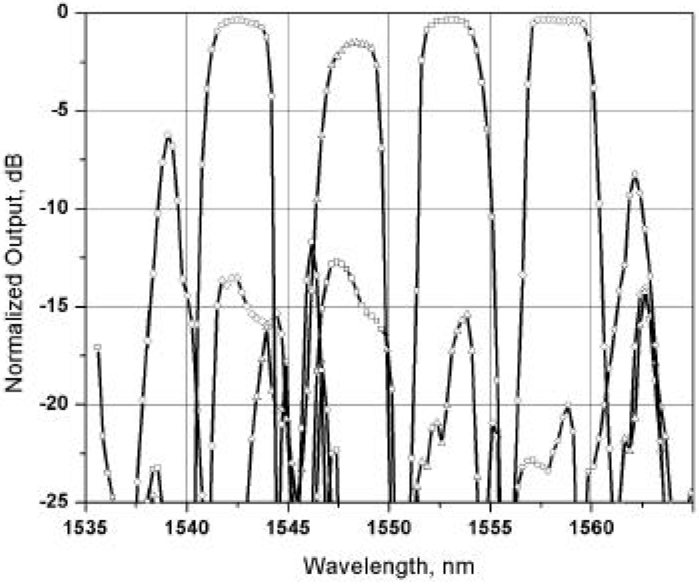

Fig. 3. Simulation of PBQC demux with significant cross-talk.

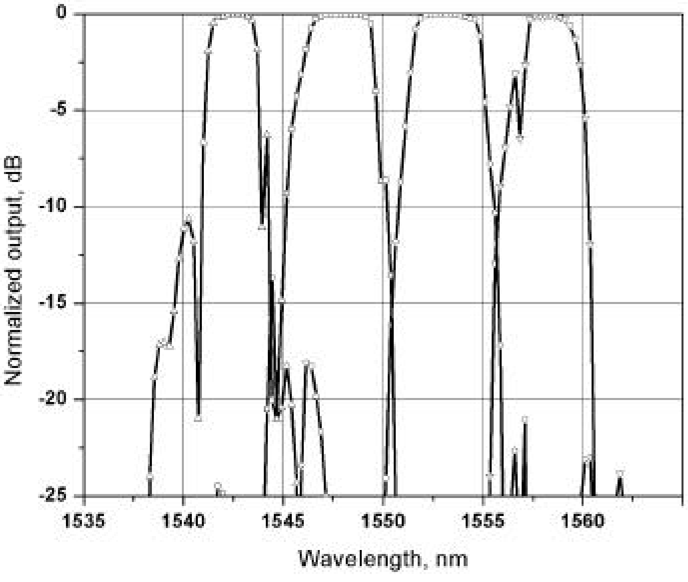

Fig. 4. Simulation of PBQC demux with reduced cross-talk.

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.

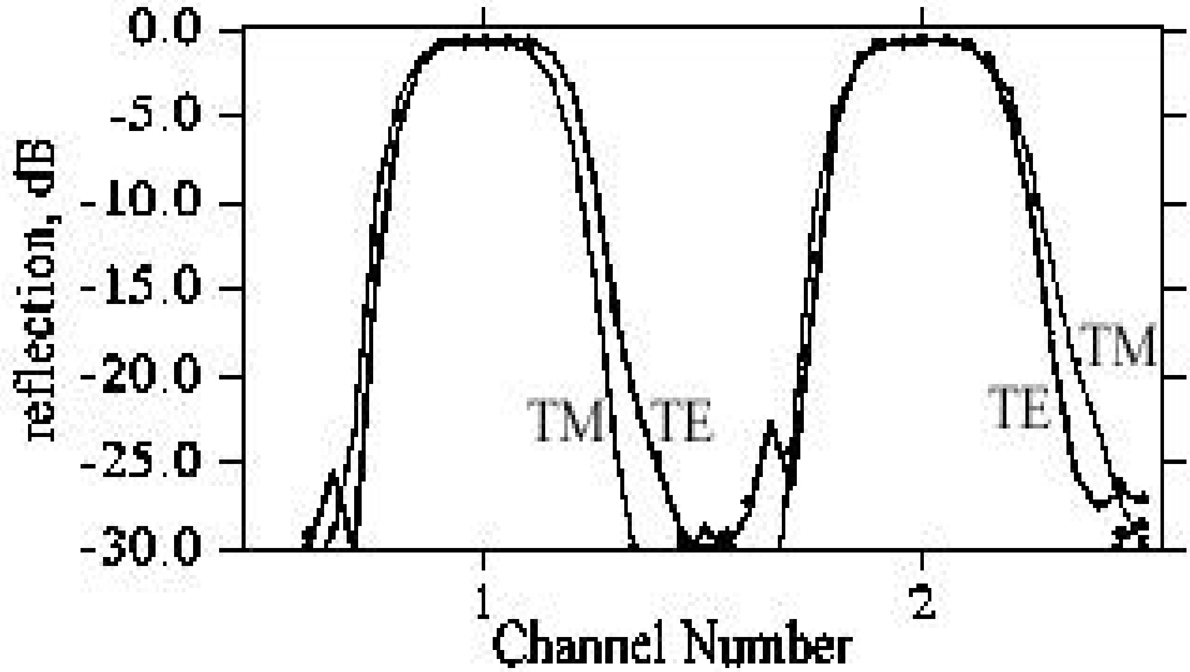

Fig.5. Two channels with minimized PDL (simulation).

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. 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.

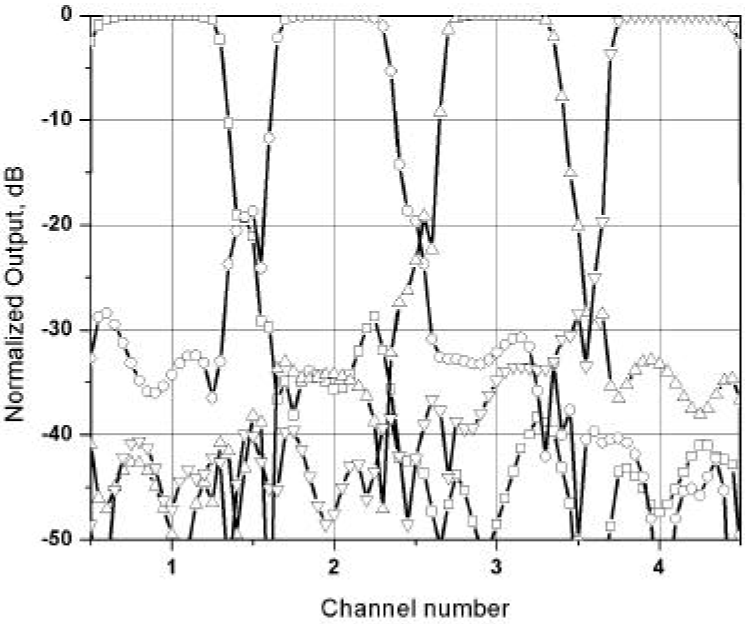

Fig. 6 Simulation of 4-channel PBCQ demux. Supergratings are disposed at both sides of the waveguide core. Spacingbetween channels equals 6.2 nm.

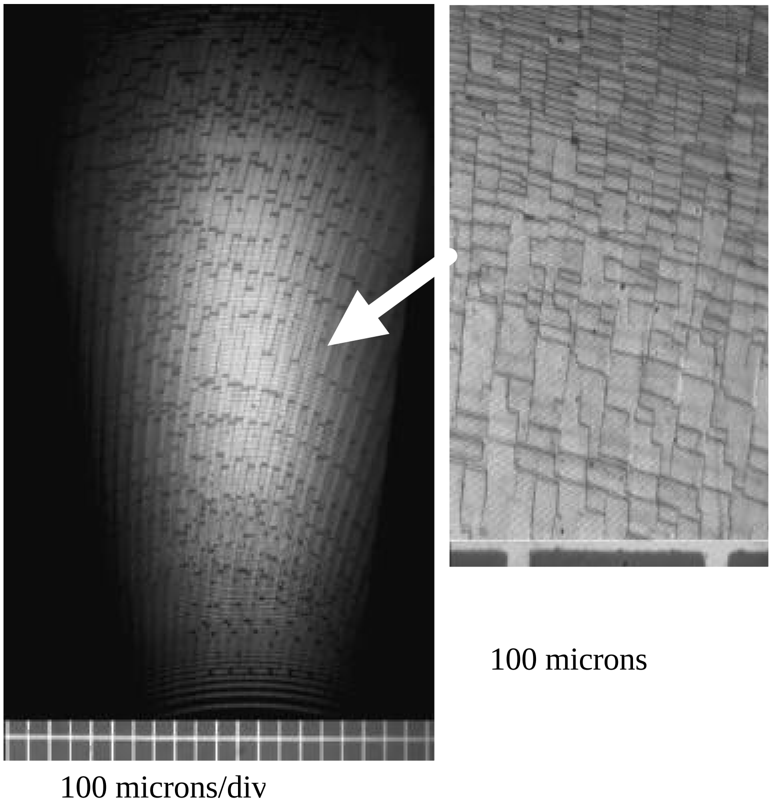

Fig.7. Optical micro photo of a 4-channel mux/demux based on PBQC technology.
Non-regularity is apparent, nonetheless there is a long-range order.

4. MANUFACTURING and TESTING of DPH MUX-DEMUX

For fabrication of the DPH structure on a planar 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. 1. 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. 7 shows an optical microphotograph of a DPH device. We also used the 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.

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 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% after passing a polarizer is directed to a tested chip (DUT). Light is focused with a system of micro-objectives onto the edge of investigated chip, the FWHM of focal spot being about 3.5 micrometer. 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 is 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. The testing setup optical scheme is presented in Fig. 8.

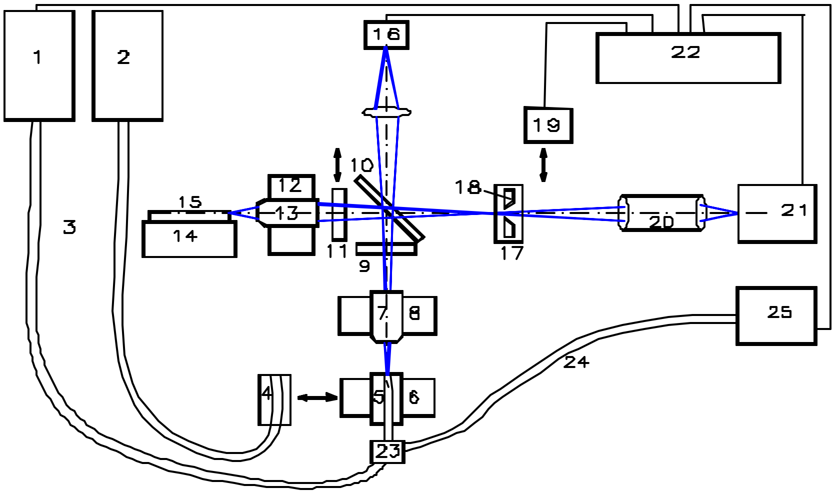

Fig. 8. Testing setup optical scheme: 1 - Tunable IR Laser, 2 - He-Ne Laser, 3, 24 - Single Mode Fibers, 4,5 - Fiber Holders, 6,8,12,14,17 – XYZ Stages, 7,13 – Microobjectives, 9 – Polarizer , 10 – Pellicle, 11 - l/2 Wave Plate, 15 – DUT, 16,19 - Power Meters, 18 - Iris Diaphragm, 20 - Relay Lens, 21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

Some results of testing are shown below in Fig. 9-11. Figures 9and 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 channels. 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 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 those shown on the graph since some measurement artifacts contributed in it’s values as we know now. Pigtailing should decrease those effects significantly.

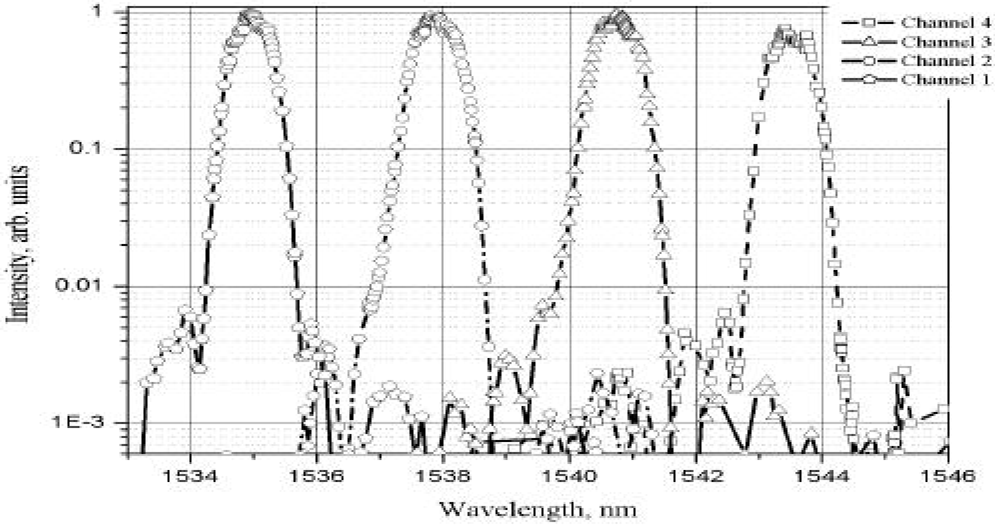

Fig. 9. Transfer functions of 4- channel devices.

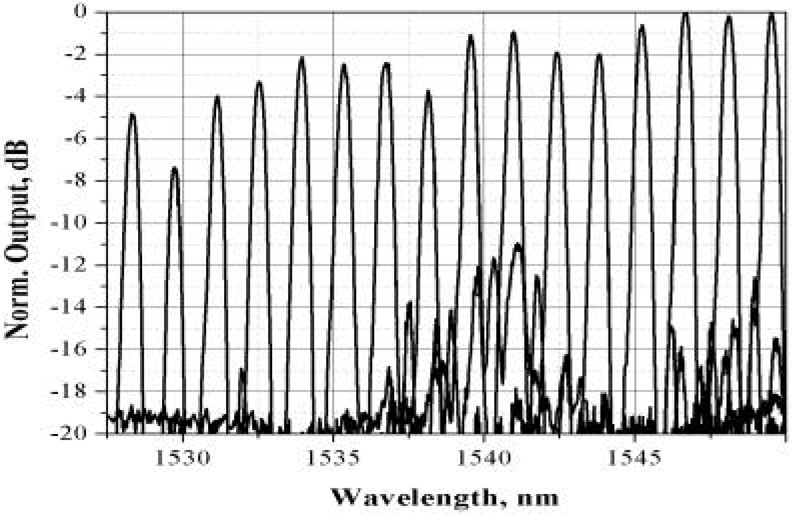

Fig. 10. Transfer functions of 4- and 16-channel devices.

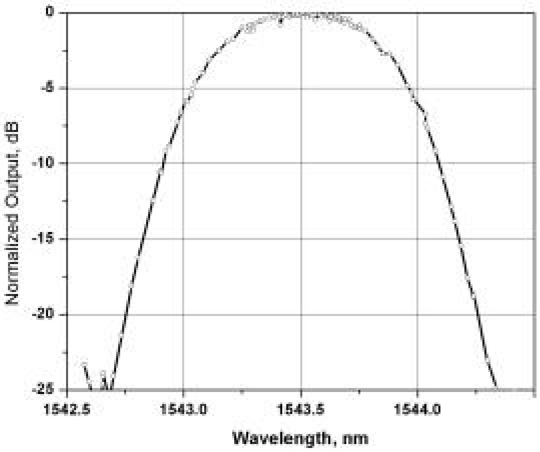

Fig.11. Four-channel device. Transfer function of one of the channels.

5. CONCLUSIONS

The possibilities of Digital Planar Holography (DPH) for designing complicated optical circuits on a single planar waveguide pllatform are considered. The new DPH-technology for integrated optical devices is proposed, designed, developed, and tested. The developed 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 at exists only for a specially desined directions. A demonstration vehicle of DPH is a flat-top planar mux/demux. By stopping the focal spotat the device output, a flat-top transfer function can be achieved without 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. 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 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.

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