Tunable integrated optical filter made of a glass ion-exchanged waveguide and an electro-optic composite holographic grating

A. d'Alessandro,[1] D. Donisi,[1] L. De Sio,[2] R. Beccherelli,[3] R. Asquini,[1] R. Caputo,[2] and C. Umeton[2]

[1]Dipartimento di Ingegneria Elettronica, Sapienza Università di Roma, Via Eudossiana 18, 00184 Rome, Italy
[2]LICRYL (Liquid Crystals Laboratory), National Institute for the Physics of Matter (INFM-CNR), Center of Excellence CEMIF.CAL and Department of Physics University of Calabria, 87036 Arcavacata di Rende (CS), Italy
[3]Consiglio Nazionale delle Ricerche – Istituto per la Microelettronica e Microsistemi (CNR-IMM), 00133 Rome, Italy
**Corresponding author: antonio.dalessandro@uniroma1.it*

Abstract: We report the fabrication and the optical characterization of a hybrid tunable integrated optical filter. It consists of a diffused ion-exchanged channel waveguide on a borosilicate glass substrate with a cover of the same glass to form a gap filled with a holographic grating. The grating morphology, called POLICRYPS (POlymer LIquid CRYstal Polymer Slices), is made of alternating stripes of polymer and liquid crystal acting as overlayer for the underneath waveguide. The filter structure includes aluminum coplanar electrodes to electrically control the grating properties, allowing the tunability of the filter. The electric driving power required to tune the filter obtained was in the range of submilliwatts due to the efficient liquid crystal electro-optic effect.

OCIS codes: (130.3120) Integrated optics devices; (130.2755) Glass waveguides; (130.7408) Wavelength filtering devices; (230.1950) Diffraction gratings; (230.1480) Bragg reflectors; (230.2090) Electro-optical devices

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References and links

1. L. V. Natarajan, D. P. Brown, J. M. Wofford, V. P. Tondiglia, R. L. Sutherland, P. F. Lloyd, and T. J. Bunning, "Holographic polymer dispersed liquid crystal reflection gratings formed by visible light initiated thiol-ene photopolymerization," Polymer **47,** 4411-4420 (2006).
2. R. Caputo, L. De Sio, A. Veltri, C. Umeton, and A. V. Sukhov, "Development of a new kind of switchable holographic grating made of liquid crystal films separated by slices of polymeric material," Opt. Lett. **29,** 1261-1263 (2004).
3. A. d'Alessandro, R. Asquini, C. Gizzi, R. Caputo, A. Veltri, C. Umeton, and A. V. Sukhov, "Electro-optic properties of switchable gratings made of polymer and nematic liquid crystal slices," Opt. Lett. **29,** 1405-1407 (2004).
4. R. Caputo, L. De Sio, A. Veltri, C. Umeton, and A. V. Sukhov, "POLICRYPS switchable holographic grating: a promising grating electro-opitcal pixel for high resolution display application," J. Disp. Technol. **2,** 38-51 (2006).
5. V. Barna, R. Caputo, A. De Luca, N. Scaramuzza, G. Strangi, C. Versace, C. Umeton, R. Bartolino, and G. M. Price, "Distributed feedback micro-laser array: helixed liquid crystals embedded in holographically sculptured polymeric microcavities," Opt. Express **14,** 2695-2705 (2006), http://www.opticsexpress.org/abstract.cfm?id=88986
6. A. d'Alessandro and R. Asquini, "Liquid crystal devices for photonic applications: state of the art and future developments," Mol. Cryst. Liq. Cryst. **398**, 207-221 (2003).
7. R. Asquini, A. Fratalocchi, A. d'Alessandro, and G. Assanto, "Electro-optic routing in a nematic liquid-crystal waveguide," Appl. Opt. **44,** 4136-4143 (2005).
8. L. Sirleto, G. Coppola, G. Breglio, G. Abbate, G. C. Righini, and M. J. Oton, "Electro-optical switch and continuously tunable filter based on a Bragg grating in a planar waveguide with a liquid crystal overlayer," Opt. Eng. **41,** 2890-2898 (2002).
9. D. C. Zografopoulos, E. E. Kriezis, B. Bellini, and R. Beccherelli, "Tunable one-dimensional photonic crystal slabs based on preferential etching of silicon-on-insulator," Opt. Express **15**, 1832-1844 (2007), http://www.opticsinfobase.org/abstract.cfm?URI=oe-15-4-1832W.

#92039 - $15.00 USD Received 23 Jan 2008; revised 27 Mar 2008; accepted 13 May 2008; published 9 Jun 2008

10. I. Fujieda, O. Mikami, and A. Ozawa, “Active optical interconnect based on liquid-crystal grating,” Appl. Opt. **42,** 1520-1525 (2005).
11. L. H. Domash, Y. M. Chen, P. Haugsjaa, and M. Oren, “Electronically switchable waveguide Bragg gratings for WDM routing,” in *Proceedings of IEEE/LEOS Summer Topical Meetings on Vertical-Cavity Lasers/Technologies for a Global Information Infrastructure/WDM Components Technology/Advanced Semiconductor Lasers and Applications/Gallium Nitride Materials, Processing, and Devices* (Institute of Electrical and Electronics Engineers, New York, 1997), paper ThA5, pp. 34-35.
12. W. Warzanskyj, F. Heisemann, and R. C. Alferness, “Polarization-independent electro-optically tunable narrow-band wavelength filter,” Appl. Phys. Lett. **53,** 13-15 (1988).
13. D. A. Smith, R. S. Chakravarthy, Z. Bao, J. E. Baran, J. J. Jackel, A. d’Alessandro, D. J. Fritz, S. H. Huang, X. Y. Zou, S. M. Hwang, A. Willner, and K. D. Li, ”Evolution of the acousto-optic wavelength routing switch,” J. Lightwave Technol. **14**, 1005-1019 (1996).
14. T. A. Birks, P. St. J. Russell, and D. O. Culverhouse, “The acousto-optic effect in single-mode fiber tapers and couplers,” J. Lightwave Technol. **14**, 2519-2529 (1996).
15. J. Zou, F. Zhao, and R. T. Chen, “Two-step K+–Na+ and Ag+–Na+ ion-exchanged glass waveguides for C-band applications,” Appl. Opt. **41**, 7620-7626 (2002).
16. L. De Sio, R. Caputo, A. De Luca, A. Veltri, C. Umeton, and A. V. Sukhov, “In situ optical control and stabilization of the curing process of holographic gratings with a nematic film-polymer-slice sequence structure,” Appl. Opt. **45**, 3721-3727 (2006).
17. J. Li, S. T. Wu, S. Brugioni, R. Meucci, and S. Faetti, “Infrared refractive indices of liquid crystals,” J. Appl. Phys. **97**, 73501-73505 (2005).
18. H. Nishihara, M. Haruna, and T. Suhara, *Optical Integrated Circuits* (McGraw-Hill, 1989), Chap. 4.
19. J. Frantz, J. Carriere, Y. Enami, R. Kostuk, S. Honkanen, D. Mathine, and N. Peyghambarian, “Selectively buried ion-exchanged waveguides as an interface to electro-optic polymers," *OSA Optical Fiber Conference*, (Optical Society of America, 2003), paper WD1.
20. D. A. Smith, A. d’Alessandro, J. E. Baran, and H. Hermann, “Source of sidelobe asymmetry in integrated acousto-optic filters,” Appl. Phys. Lett. **62**, 814-816 (1993).

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1. Introduction

Research of novel electro-optic materials has been driven to fabricate low cost optoelectronic devices for different optical system applications. An important requirement is also low power consumption especially for applications such as fiber-to-the-home or fiber-to-the-curb systems, in order to keep system costs low. Optical filters with high performance to cost ratio are required in spectral analysis modules used in fiber optic sensor systems as the interrogation systems of fiber Bragg grating sensors used for structural health monitoring.

Recently composite materials have become quite attractive for their efficient electro-optic effect. Among these novel composites made of polymer and liquid crystal (LC) such as H-PDLC (Holographic Polymer Dispersed Liquid Crystals) [1] and POLICRYPS (POlymer LIquid CRYstal Polymer Slices) [2] have been developed to make very efficient electro-optic Bragg gratings operating in a free-space configuration for fiber-optic systems [3] and display applications [4]. POLICRYPS have been also used as waveguides to make tunable microlaser sources [5]. Moreover the idea of using liquid crystals as efficient electro-optic material is quite interesting because of the possibility to make integrated optical switches [6], routers [7], tunable devices [8][9], and beam deflectors for optical interconnects using slab waveguides [10]. A PDLC electro-optic grating in combination with an half-coupler containing a single mode fiber has been proposed to make electronically switchable waveguide Bragg grating for wavelength division multiplexed (WDM) systems [11].

Since the refractive index of LC used for composite gratings ranges from 1.45 to 1.6 they can be combined with either polymeric or glass optical waveguides which are simple and cheap to fabricate. Such an hybrid approach can be proposed as a low cost alternative to the different technologies developed in the past decades such as electro-optically [12] or acousto-optic tunable filters/switches on $LiNbO_3$ [13] or in fibers [14]. In this paper the first demonstration of an optical tunable filter made of a novel Bragg holographic grating with a POLICRYPS morphology written over a channel ion-exchanged waveguide diffused in BK7 glass is described. The novelty of such an integrated optic tunable filter with respect to the state of the art is the combination of an organic electro-optic composite grating structure with a passive glass channel waveguide realized with a simple and low cost technology. In

#92039 - $15.00 USD Received 23 Jan 2008; revised 27 Mar 2008; accepted 13 May 2008; published 9 Jun 2008

particular the advantages of using a channel rather than slab waveguides or optical fibers are well-known: possibility to design planar lightwave circuits with various paths and above all the possibility to obtain easy fiber optic coupling for device packaging. Ultimately the novel hybrid technological approach presented in this paper can be used to make a large variety of low cost electro-optically controllable components on glass such as add-drop multiplexers, optical switches and so on.

Main details of the fabrication process and the preliminary results of the optical response of the integrated optical filter proposed here are reported.

2. Sample fabrication and working principle

The structure of the integrated optical filter based on POLICRYPS is sketched in Fig. 1. It includes a borosilicate BK7 substrate including a channel in-diffused waveguide. A POLICRYPS grating is placed as an overlayer of the waveguide between the substrate and a glass cover. Coplanar electrodes are patterned aside the waveguide to drive the liquid crystal molecules between the polymer walls of the composite grating like in in-plane switching LC flat panel displays. A gap of 15 µm between the electrodes, where the waveguides are located, is wide enough to avoid optical losses induced by influence of aluminum on the light propagation in the optical channels.

The fabrication of the device started with the preparation of the optical waveguides on a BK7 glass substrate. Channel in-diffused waveguides were fabricated by using double ion exchange in melted salts [15]. After cleaning the substrate, a first ion exchange Na^+-K^+ was performed in melted KNO_3 for 80 min at 400 °C. An aluminum mask was then deposited by e-beam vacuum evaporation and 6 µm channels apertures were obtained by wet-etching process in KOH. A second ion-exchange Ag^+-Na^+ was then performed at 330 °C for 4 hours. Thermal annealing at a temperature of 300 °C for 24 hours was then performed to have a more uniform distribution of Ag^+ and consequently of the refractive index. This annealing also reduces significantly propagation losses due to silver colloids. We have indeed measured a decrease of the losses from 4 $dBcm^{-1}$ before annealing to less 1 $dBcm^{-1}$ after annealing.

A second lithographic step was carried out for partial removal of the same masking aluminum to obtain autoaligned coplanar electrodes with a length of about 1 cm along the optical waveguide. Hence costly vacuum processes are limited to one only.

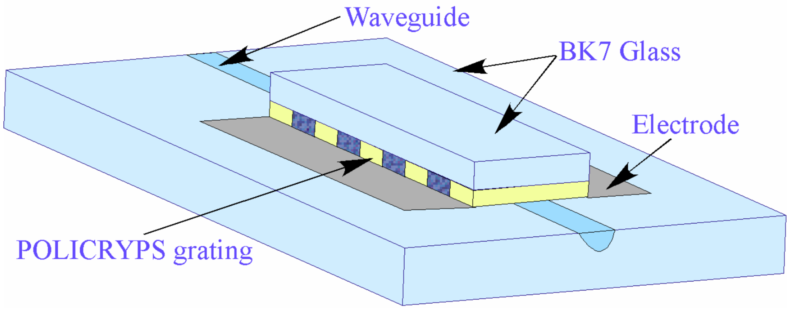

Fig. 1. Schematic of the optical filter using composite grating made of polymer and liquid crystal (POLICRYPS) over an ion-exchanged waveguide.

A device was then assembled by placing the BK7 cover on top of the processed substrate including the optical channel waveguides by using ball spacers mixed to the UV-curable glue to realize a gap of about 5 µm. The assembled device is then filled by capillarity with a mixture of 70% of UV-curable pre-polymer NOA61 and 30% of E7 nematic LC (NLC). Then the standard POLICRYPS grating writing process [2] was performed on a stabilized setup [16]. The cell was then placed in a hot stage holder to carry out the optical writing at the temperature of about 63 °C above the nematic-isotropic transition phase of the NLC and pre-

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polymer which is about 61 °C. The writing process consisted in exposing the cell to an interference pattern of two UV continuous wave laser beams at the wavelength of 351 nm with a power density of about 10 mW/cm^2. During exposure the pre-polymer is being cured and slides of polymer separated by NLC are formed. The pitch of the grating fabricated for the optical filter was estimated to be about 2.55 µm, but the writing set-up can be calibrated to obtain grating periods down to 0.5 µm. Figure 2 shows a microscope image of a test prototype without electrodes which shows the grating aligned with its wave vector parallel to the underneath optical waveguide. Optical characterization of the sample without electrodes showed that when no voltage is applied the LC molecules are aligned perpendicular to the polymer stripes. Thus the NLC behaves as an optically anisotropic medium with its optical axis along the director, which represents the average orientation of the LC molecules. The optical axis or extraordinary axis is also called slow axis since the extraordinary refractive index n_e= 1.689 measured at the wavelength of about 1.55 µm for pure E7 [17] is higher than ordinary refractive index n_o = 1.5 of the NLC related to any direction which is perpendicular to the NLC director. Thus this direction represents the fast or ordinary axis. Since the refractive index of the polymer at the wavelength of 1.55 µm is n_p= 1.5419, the refractive index mismatch between n_o and n_p induces an active grating therefore a filtering function for the light propagating through the channel waveguide is expected. The refractive index mismatch can be tuned by applying an electric field by means of the coplanar electrodes inducing a reorientation of the NLC molecules in the plane of the substrate and hence of the refractive index seen by the TE-like mode confined in the single-mode ion-exchanged glass waveguide.

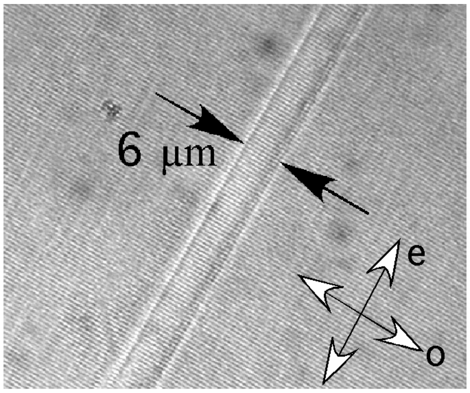

Fig. 2. Microscope image of the POLICRYPS grating written over a 6 µm wide waveguide. The white arrows below indicate the orientations of the fast or ordinary (o) axis and of the extraordinary (e) or slow axis of the NLC.

An average effective refractive index of the waveguide of about n_{eff} = 1.52 was computed by using a mode solver. The latter is fed with a complementary error function profile as refractive index of the glass waveguide [15] and a perturbation of the overlaying grating is considered when no external voltage is applied. By considering a grating pitch of about Λ = 2.55 µm, a Bragg wavelength λ_B= 2 n_{eff} Λ /m at about 1550 nm, in the C-band of fiber optic systems, is expected for the fifth order (m= 5) of diffraction.

3. Experimentals and discussion

The characterization of the tunable filter was carried out by using the experimental set-ups of Fig. 3 to detect the optical transmitted and back-reflected spectra of the filter both with and without applied electric field. After facets polishing and wire bonding the electrodes, input and output endfaces of the sample were fiber butt-coupled.

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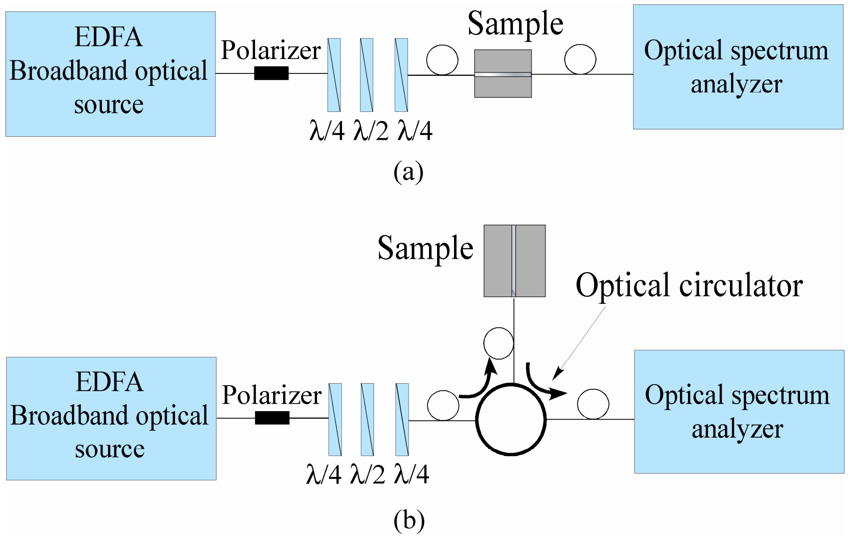


(a)

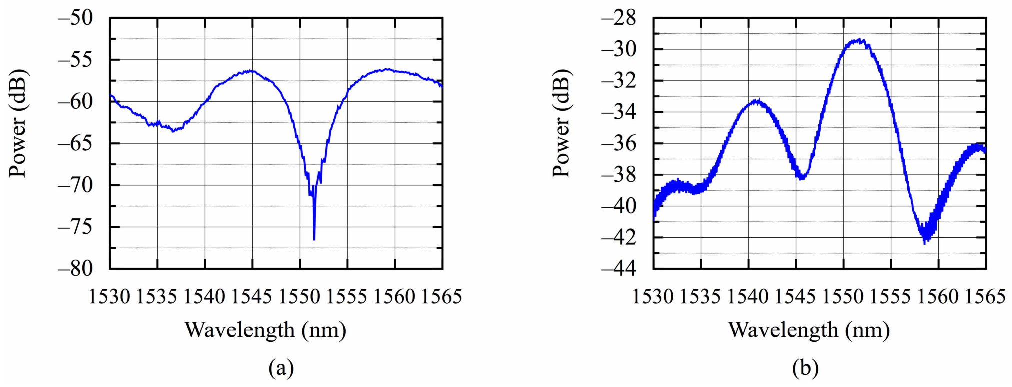
(b)

Fig. 3. Set-ups to measure the transmitted (a) and the reflected spectra (b) of the filter.

The optical characterization was performed by launching into the waveguide input the spontaneous emission of an erbium-doped fiber amplifier, whose broad spectrum extends over the whole C-band from 1530 nm to 1565 nm and is flat from 1540 nm. The input light polarization was TE after passing through an in line fiber polarizer and a polarization controller made of three rotating waveplates. As shown in Fig. 3a, the transmitted spectra were detected by the optical spectrum analyzer after collecting the waveguide output light. In order to detect the reflected spectra an optical circulator was used as shown in Fig. 3b.

Both transmitted and reflected optical responses normalized with respect to the EDFA spectrum are plotted in Fig. 4. Figure 4a shows the transmitted notch spectrum with a maximum depletion of about 20 dB at the wavelength of about 1552 nm, close to the wavelength estimated by applying the Bragg law. At the same wavelength the back-reflected pass-band response shows its transmission peak as Fig. 4b reports, with an FWHM bandwidth of about 5 nm. It was observed that the optical response, both in reflection and in transmission, was polarization insensitive confirming that the alignment of the NLC molecules was along the direction of propagation so the refractive index mismatch between n_o and n_p is seen by any light polarization.

Some discrepancies between the two spectra of Fig. 4 and the corresponding spectra of an



(a)

(b)

Fig. 4. Transmitted (a) and reflected spectra (b) of the filter normalized with respect to the EDFA spectrum.

ideal Bragg reflector can be noticed by observing the sidelobes intensity and the wavelengths in which they occurs. In theory for normalized transmission T(λ) and reflection R(λ) spectra, T(λ)+R(λ)= 1 holds. We argue that the different behavior of our device from an ideal Bragg reflector is caused by the non-uniform power spectral distribution of the transmitted and back-reflected substrate modes. These substrate modes are excited by the strong coupling effect of the grating. As several different modes are likely to be excited, multibeam waveguide-substrate and waveguide-cladding coupling occurs in the filter structure [18]. Multibeam coupling is generated because the grating operates at the fifth order of diffraction and because of the values of the refractive indexes of substrate, overlayers (grating and upper glass) and channel waveguide. The substrate modes are finally collected by the input and output optical fibers along with the guided mode. In particular, the set of transmitted substrate modes causes out of band resonances at wavelengths which are different from the wavelengths of the outband resonances caused by the set of the back-reflected substrate modes. Such resonances overlapped to the waveguided spectra result in a non-uniform power distribution over the entire spectral range of the filter optical response. Moreover, Fig. 4 also shows that there is a large difference of over 20 dB between the peak of the reflected and of the transmitted power. Among the many reasons that may cause such a large difference detected in this preliminary measurements of our first filter prototype, we believe that the main contribution is given by the total power of the substrate modes collected by the input fiber which is much higher than the power of the substrate modes collected by the output optical fiber with the waveguided filtered light. Another contribution to the difference between the transmitted and the reflected power is also given by the additional back-reflected light at the input fiber-sample interface. The optical insertion losses of this first sample realized primarily for preliminary concept demonstration have not been evaluated precisely but they are quite high, in the order of 15 dB. Such high losses are due to both multibeam coupling and non-adiabatic transition of light from the channel waveguide to the POLICRYPS overlayer, induced by an average refractive index of the grating which is still quite high compared with the refractive index of the optical waveguide [19]. New samples with a 0.5 cm rather than 1 cm long grating operating at the first order of diffraction and with novel NLC-prepolymer mixtures are currently under study to reduce both multibeam coupling and optical losses.

As a voltage was applied to the coplanar electrodes the filter optical response was tuned. A square-wave voltage of 1 kHz frequency was applied at different amplitudes from 10 to 40 V. This corresponds to an electric field of about 0.7-2.7 V/µm for the chosen gap of 15 µm between the electrodes. Figure 5 shows the overlap of the optical pass-bands of the filter obtained as the voltage was changed. A tuning range of about 4 nm was achieved but only for TE light. In fact the up-shift of the peak wavelength is due to the increase of n_{ave} as a consequence of an higher refractive index of the NLC “seen” by TE light according to the well-known formula:

$$n_{LC}(\theta) = \frac{n_e n_o}{\sqrt{n_0^2 \sin^2\theta + n_e^2 \cos^2\theta}} \tag{1}$$

where θ is the voltage dependent tilt angle of the NLC director with respect the direction of propagation.

The strong asymmetry of the reflected response indicates an imperfect uniformity of the POLICRYPS structure along the waveguide as explained for analogous filters based on Bragg gratings [20]. Such a lack of uniformity is in part due to the residuals of prepolymer in the liquid crystal slices, which also influences the value of the birefringence of the liquid crystal as observed in preliminary observations by means of the polarized microscope. In fact a 4 nm tuning range is less than the tuning range expected from the E7 birefringence. Investigations on the perturbation of the value of the E7 NLC birefringence in the POLICRYPS structure are under way.

When voltage was applied the current absorption was measured by using a precision amperometer in order to calculate the power consumption of the filter. A current with an effective value of few tens of μA was measured, indicating a very low level of absorption by the composite electro-optical grating. Such a low current supplied indicates that the filter requires only a few hundreds of μW to be driven for the whole tuning range.

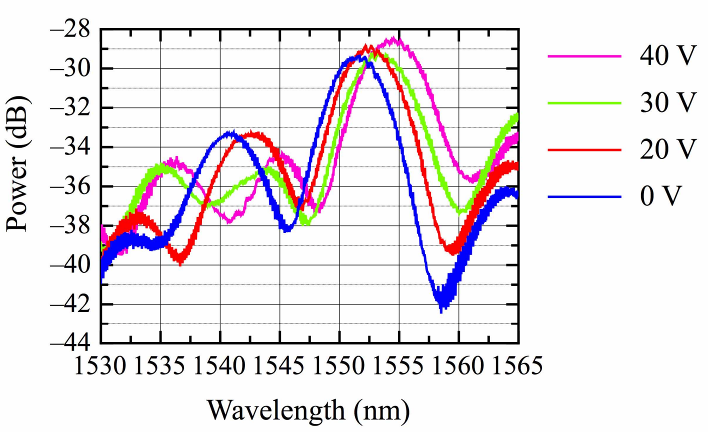


Fig. 5. Overlapped reflected spectra obtained by varying the applied voltage, normalized with respect to the EDFA spectrum.

4. Conclusions

We demonstrated a novel hybrid Bragg integrated optic filter on glass by combining ion-exchanged channel waveguides and POLICRYPS composite holographic gratings using easily commercially available materials. The fabrication process is quite simple and preliminary filter performance are promising for low cost fiber optic systems. Without optimization the first prototype presented in this paper showed a passband with about 20 dB signal suppression at the Bragg wavelength. A continuous tuning range of 4 nm was observed by applying a few tens of volt corresponding to an electric field less than 3 V/μm and with a very low current absorption resulting in a submilliwatt driving power. The device can be optimized in terms of grating pitch to obtain operation at the first order of diffraction, better uniformity, reduction of optical losses and apodization to meet requirements for a large variety of fiber optic systems both in the field of telecom and sensing.

Acknowledgments

The authors are grateful to Mr. Marco Renzetti for enlightening discussions and for his precious support in the measurements. This work was supported by PRIN 2006 Project Prot. N. 2006022132_002 of the Italian Ministry of University and Research.

#92039 - $15.00 USD Received 23 Jan 2008; revised 27 Mar 2008; accepted 13 May 2008; published 9 Jun 2008