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ScienceDirect
Optics Communications 278 (2007) 329–333
OPTICS COMMUNICATIONS
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Liquid crystal enabled multi-channel power equalizer and stabilizer

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Received 19 March 2007; received in revised form 28 May 2007; accepted 7 June 2007

Abstract

Automatic power equalization and stabilization of a liquid crystal enabled channel-selectable optical demultiplexer is demonstrated. The variation among output signals from different channels was reduced from ~10 dB to 0.15 dB with feedback control. The minimum ripple level of a single channel is ~0.05 dB. As a variable optical attenuator (VOA), the attenuation range of the device is ~12.6 dB.
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PACS: 06.30.Bp; 07.60.Ly

Keywords: Demultiplexer; Liquid crystal; VOA; Equalizers

1. Introduction

In a wavelength division multiplexing (WDM) optical communication system, power non-uniformities over the channels occur due to the non-flat gain profiles of optical amplifiers. To restore the power balance of the WDM channels, channel equalizers or variable optical attenuators (VOA) are often employed. A number of different designs of dynamic VOA or power equalizer have been implemented in the past, using technologies such as micro-opto-mechanical modulator array [1], Mach–Zender interferometers [2], arrayed waveguide gratings [3], acousto-optic tunable filters [4], and $LiNbO_3$ (LN) phase shifter array [5], and so on. Liquid crystal (LC) technology has also been drawing a lot of attention for WDM systems. Parker et al. [6] controlled five WDM channels spaced by 4 nm using in-line liquid crystal spatial light modulator (LC-SLM), reducing an input power variation of 8.5 dB down to 0.3 dB. A multiple-stage LC optical harmonic equalizer, each stage of which consisting of a LC harmonic filter to adjust the wavelength shift and a LC attenuator to adjust the amplitude was reported [7]. Low-loss multi-channel VOAs using polymer-network LC integrated on planar light wave circuits have been reported [8]. In a follow-up work, Hirabayashi and Amano [9] reported suppression of power fluctuations to 0.5 dB using the LC-VOA with a dithering feedback circuit. Recently, we reported a liquid-crystal-based 16-channel demultiplexer (LC-multi-DEMUX) with channel switching or routing function [10]. It is based on our tunable laser design [11,12]. It differs from the previous design in two aspects: (1) the LC-SLM is placed at the focal plane of the folded telescopic grating system; (2) every other pixel of the LC-SLM was matched to one multi-mode fiber channel. The variation between different channels can be reduced from ~10 dB to less than 0.5 dB by manually adjusting the voltage addressing the pixels in the LC-SLM used. In this paper, we demonstrate automatic power equalization and stabilization of output signals from four channels of the LC-multi-DEMUX. The variation between output signals

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doi:10.1016/j.optcom.2007.06.020

from different channels is reduced from ~10 dB to 0.15 dB. It can be further improved to be less than 0.02 dB.

2. Devices construction and operation principles

Construction of the device and the instrumentation for measurements are shown schematically in Fig. 1a. Detailed description of the device and its operation principle can be found in our previous paper on the LC-multi-DEMUX [10]. In short, the first-order-diffracted signal light (Erbium-doped fiber amplifier (EDFA)) from the grating (1100 lines/mm) was collected by a lens (focal length, $f = 204.6$ mm), focused on to the LC-SLM and coupled into a 16-channel array of multi-mode optical fibers. The channel spacing is 100 GHz, corresponding to the International Telecommunication Union (ITU) grid. Dynamic channel management was accomplished by using in-line LC-SLM and the output powers of the channels can be adjusted individually, enabling the VOA mode of the LC-multi-DEMUX. Here we demonstrate a four-channel version of the automatic power equalizer and stabilizer. The output power of each channel as detected by the photodiodes (PD) was fed to a personal computer (PC). The control circuit of the LC pixels is shown in Fig. 1b. We adjusted the driving voltages of the pixels in 512 steps by a parallel connection of two 256-step-adjustable, 5 kΩ digital variable resistors (DVR, GS6267D, Linkas Corp., Taiwan). The resistance of DVR can be set or read by 3-wire (EN: enable control input; CLK: clock control input; Din: data input) control methods. The power fluctuations among the four channels can then be controlled to a desired constant power level by using a feedback control loop. The resistance of the DVR is variable and can be controlled by digital signals from a personal computer (PC) or other sources, to modulate the voltage applied on the LC-SLM. The GS6267D is an IC which includes 2 sets of variable resistors (VRs). Each set of VR, with the total resistance of 10 kΩ, is constructed by 256 identical resistor elements. The resolution of the VR can be set to be 10 kΩ/256 steps, or 20 kΩ/512 steps (by connecting the two sets of VR in series), or 5 kΩ/512 steps (by connecting the two sets of VRs in parallel). By combining a fixed high resistor (5 kΩ) and the DVR in series, the applied voltage can be varied in the linear operating range of our LC-SLM (2–4 V_{rms} for 0–80% transmittance). In principle, the ripple level can be further improved by increasing the resolution of the DVR used to 4096 steps. To achieve a resolution of 4096 steps by using the DVR used in this work,

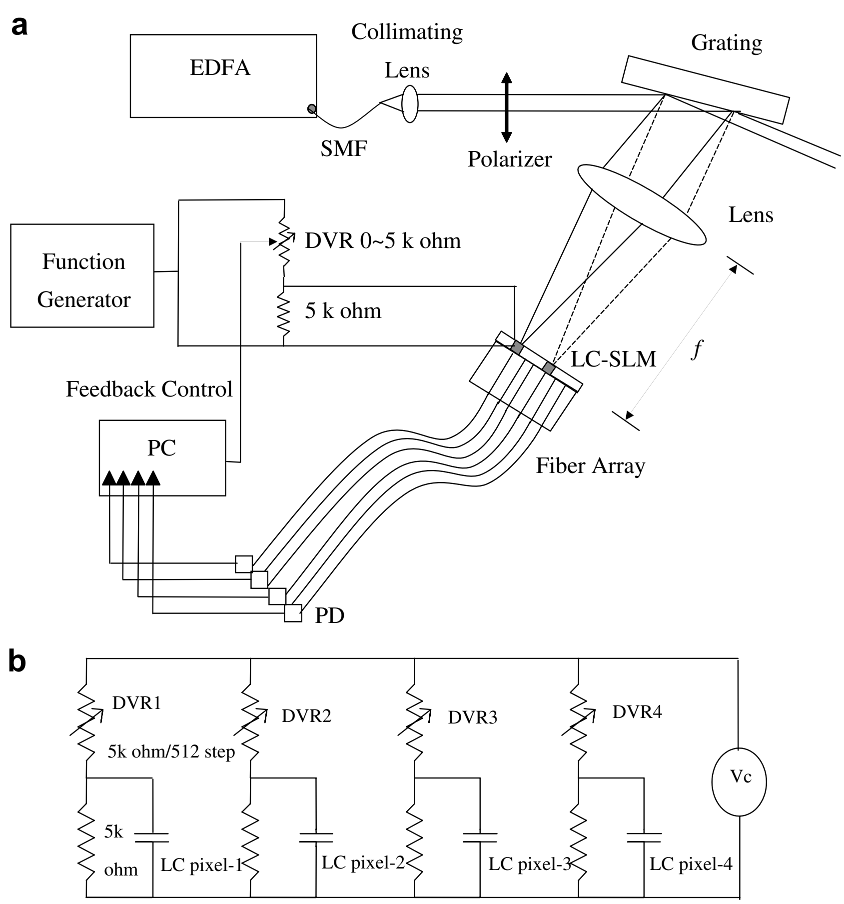

Fig. 1. (a) Experimental setup: EDFA, erbium-doped fiber amplifier; SMF, single-mode fiber; *f*, focal lens; OSA, optical spectrum analyzer; DVR, digital variable resistor; PC, personal computer; PD, photodiode. Fig. 1. (b) Control circuit for power equalization and stabilization.

one can connect eight pieces of DVR in parallel for one channel. The modulation range of each channel of the LC-SLM, however, will be limited to the range of 3.55–4 V_{rms} This problem can also be solved by combining the DVR in series with a fixed high resistor.

3. Results and discussion

We demonstrate power equalization and stabilization of four channels of the LC-multi-DEMUX at center wavelengths of 1535.04 nm, 1538.19 nm, 1541.35 nm and 1543.73 nm, respectively. The original output powers of the four channels are −54.58 dBm, −62.05 dBm, −64.6 dBm and −61.03 dBm, respectively. The maximum power fluctuation among the four channels is about 10 dB. The insertion losses (ILs) of the different pixels of the home-made LC-SLM are in the range of 1–3 dB. The extinction ratios of the four channels, defined as ratio of the transmittance for pixels ON and OFF, range from 11.5 dB to 16.2 dB. The average extinction ratio is 12.6 dB. This represents the attenuation range of the VOA mode of the device. Yeh and Gu [13] has been shown that the transmittance of a twisted nematic liquid crystal cell depends critically on the thickness of the LC layer. Following [13], we calculate that the optimum thickness for maximum extinction ratio of the twisted NLC cell (E7 by Merck, $\Delta n = n_e - n_o = 0.22$ at $\lambda = 1550$ nm) is 6 μm. The E7 layer thickness in our device is, however, 8 μm. Thus we expect the extinction ratios or attenuation range of the present device to be lower than the ideal case. As the thickness of the LC-SLM is not uniform across the channels, different channels of our home-made device would vary somewhat in the attenuation ranges. Further, the present device is polarization sensitive with a polarization dependent loss of about 15 dB. It can be improved by using a polarization insensitive grating [14] and polarization independent polymer-dispersed LC for the LC-SLM [15]. The theoretical attenuation range of our VOA, employing polarization optics with extinction ratios of 10^5 is estimated to be better than 30 dB. The LC-multi-DEMUX is sensitive to the environmental conditions. Without any control of the device, the power fluctuation of its output was measured to be as high as 24% for a period of five hours. During this period of time, the temperature varies 1.8 °C. The power fluctuations reduced to ~2.4% when the temperature variation was controlled within 0.3 °C.

The initial value of each DVR is set at 50% of the full range (2–4 V_{rms}). Fig. 2 illustrates residue power fluctuations of signals from the four channels under feedback control for a period of 80 minutes.

The two traces in Fig. 2a–d are respectively output power of the channel as read by the PD and the corresponding step of the DVR. We set the driving voltage at 2.5 V_{rms} and the maximum allowed ripple level at 0.9%. Measured ripple levels of the four channels are 1.10% (0.05 dB), 3.48% (0.15 dB), 1.37% (0.06 dB), and 1.37%

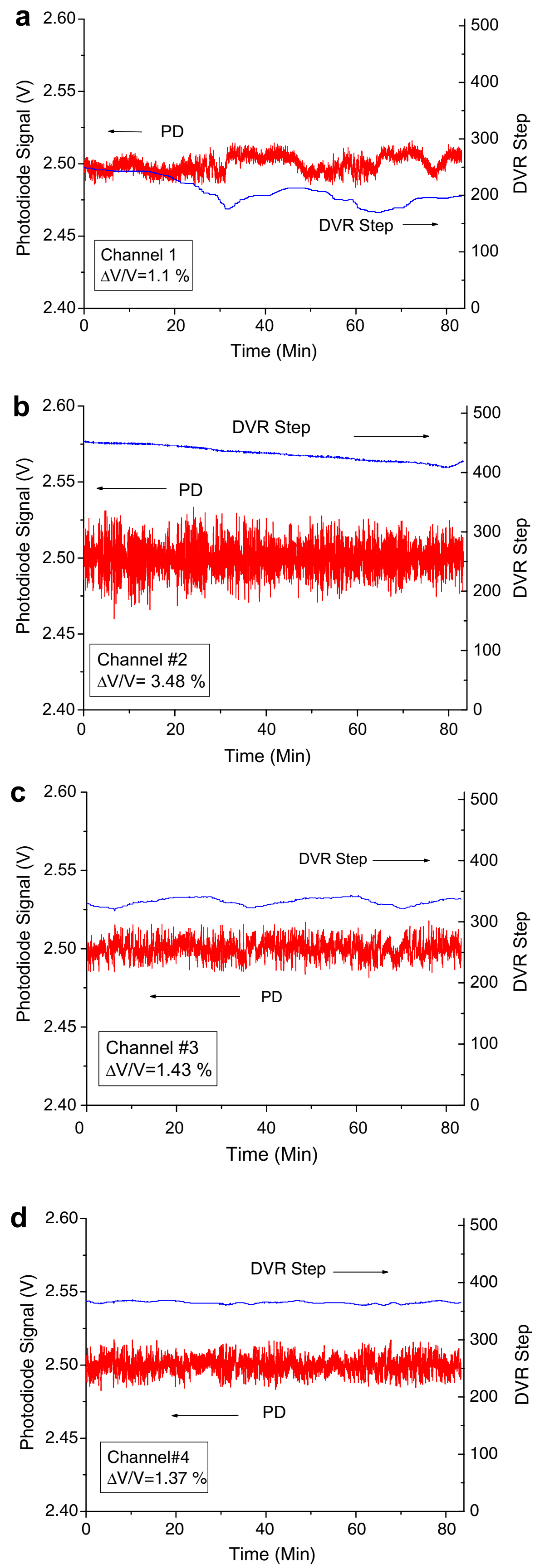

Fig. 2. The ripple levels and corresponding steps of the DVRs of the four channels (a through d) after power equalization.

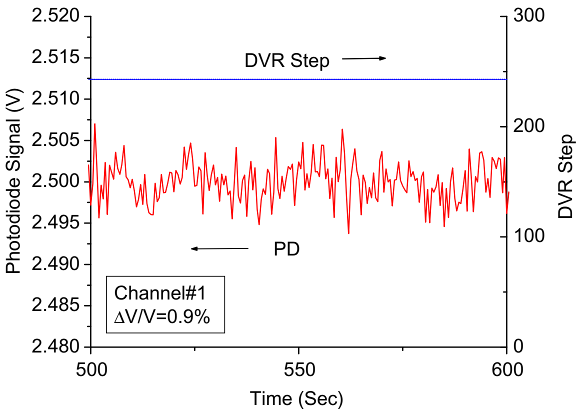

Fig. 3. The ripple level of the channel output and corresponding step of the DVRs for 100 s.

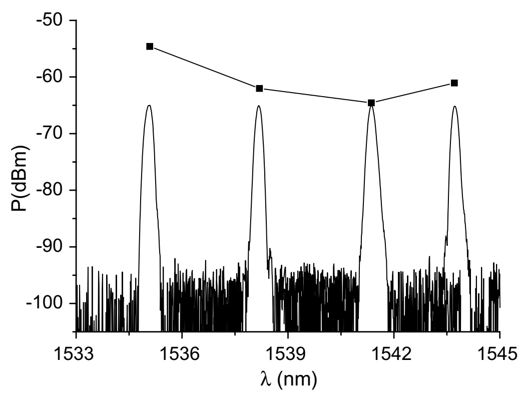

Fig. 4. Spectra of the automatically controlled and power-equalized outputs of four channels of the LC-Multi-DEMUX. The black square indicates the output power of each channel before power equalization.

(0.06 dB), respectively. The measured values are larger than the preset values. The discrepancy is due to limited resolution of the DVR (512-steps). We observed that the ripple level is as small as ∼0.3% (0.013 dB) for a short period of time of the order of 100 s. This is shown in Fig. 3.

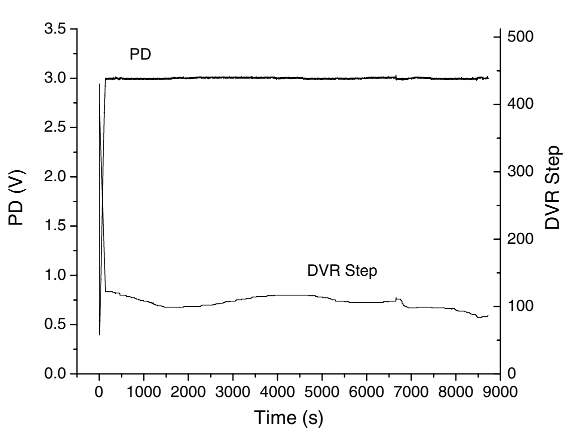

Fig. 5. Speed performance of the stabilization circuit. PD, photodiode; DVR, digital voltage divider.

During this time the state of the DVR remains at the initial value. We thus expect the ripple level of 3.48% can be improved to 0.3% by increasing the resolution of the DVR to 4096 steps.

We demonstrate the automatically power-equalized and stabilized output spectra of four channels of the LC-multi-DEMUX in Fig. 4. The output powers of the four channels before power equalization, about 10 dB, are also plotted in the figure.

By switching on an old noisy air conditioner in our laboratory, we artificially generated power fluctuations of about 5.26% in the output of the demultiplexer. The performance of the stabilization system is demonstrated. As shown in Fig. 5, it took less than two minutes to achieve power stabilization after activating the feedback control system.

4. Conclusions

We demonstrate automatic power equalization of output signals from four ITU channels by servo-controlling the driving voltages of liquid crystal pixels. The attenuation range of the VOA mode of the device is, on the average, 12.6 dB. The insertion loss of different channels ranges from 1 dB to 3 dB. The outputs of different channels are equalized to −65 dBm with variation less than 0.15 dB. These are also stabilized over a period of 80 minutes. The minimum ripple level of a single channel is ∼0.05 dB. The performance is limited by the 512-step resolution of the digital variable resistor. We believe it can be further improved to be less than 0.02 dB by increasing the resolution of the DVR used to 4096 steps.

Acknowledgements

This work was supported in part by the National Science Council (NSC) through various grants including PPAEU-II and the ATU program of the Ministry of Education, Taiwan, ROC.

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