Hybrid analog-digital design microelectromechanical systems spectral processor for simultaneous gain slope and channel equalization controls

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Abstract. To the best of our knowledge, this paper demonstrates the first hybrid analog-digital design fiber-optic spectrum processor that can simultaneously provide spectrum gain slope adjustment as well as independent channel equalization attenuation controls. © 2007 Society of Photo-Optical Instrumentation Engineers.
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1 Introduction

Wavelength division multiplexed (WDM) fiber-optic communication networks require precise optical spectrum control for high performance. Erbium doped fiber amplifiers (EDFAs) can generate varying unbalanced spectral gain response due to various factors such as amplifier cascading and varying input power levels. Hence networks use electronically adjustable EDFA gain slope adjusters to dynamically optimize spectrum profile. Here various technologies have been used including birefringent plates and Faraday rotators, tunable waveguide Mach-Zehnder couplers, and all-fiber acoustooptics.¹⁻¹² In addition, because of the real-time channel-based wavelength add and drop operations, the WDM spectrum also requires channel-based equalization. Hence, channel-based equalizers¹³⁻¹⁷ for the specific WDM band are deployed. Although the channel-based equalizer at the cost of much higher control complexity can be used for spectrum slope adjustment, this operation eats up the available attenuation dynamic range required for equalization on a per-channel basis. Hence, the goal of this paper is to propose and demonstrate the basic operation of a single spectral processor that can provide both gain slope adjustment plus high dynamic range per channel equalization controls.

Fig. 1 Proposed hybrid design analog-digital microelectromechanical systems spectral processor for simultaneous gain slope and channel equalization controls.

2 Hybrid Analog-Digital Spectral Processor Design

Recently, a hybrid analog-digital variable optical attenuator (VOA) was proposed and demonstrated.¹⁸ Here, analog tilt motion of a fiber lens (FL) was used to form an analog VOA via beam misalignment while simultaneous digital control of binary tilt state micromirrors over the spatial beam zone produced a digital VOA. Using this fundamental analog-digital controls concept, Fig. 1 shows the proposed novel spectral processor that forms a spectral gain slope adjuster and a channel-based spectral equalizer within one optical system. Specifically, Bragg direction analog tilt control of the FL coupled with the Fourier lens optical architecture interacting with a volume Bragg grating (VBG) is used to realize the analog-mode gain slope adjuster. On the other hand, digital control of micromirror binary tilt states within a Texas Instruments (TI) Digital Micromirror Device (DMDTM) is used to provide all-digital channelized equalization. Light enters and exits via a circulator *C* connected to two single mode fibers. FL is used to launch the light into the freespace system with three cylindrical lenses (*C_y*, *C_x*, *C_y*) between the DMDTM and the VBG forming an imaging system along the *y* direction and a Fourier transforming system along the *x* direction. The quarter-wave plate (QWP) is used to reduce polarization-dependent loss of the VBG. The VBG is oriented for Bragg matched operation for the mid-band wavelength λ_c . At this θ_c position, ideally, the processor has a symmetric near-flat spectral response in the chosen band as the VBG is designed for broadband high diffraction performance^{19,20} for the given telecom band and all wavelengths would operate in a retroreflection beam path geometry from the mirror plane. In practice, the DMDTM fundamentally acts as a wavelength-sensitive blazed grating and ideal retroreflective operation happens for a given wavelength such as λ_c . In contrast, the other wavelengths produce a slight (e.g., <0.2 deg) angular spread on reflection from the DMDTM to cause nonuniform coupling into FL across the wavelength band. This coupling

(a)

(b)

Fig. 2 Measured example positive gain slopes of (a) 0.67 dB/nm and (b) 1.16 dB/nm from the hybrid spectral processor. Trace horizontal scale: 3-nm divisions; vertical scale: 10-dB divisions.

nonuniformity can be minimized by proper choice of processor component specifications for a given spectral band. For optimal operations, the FL tilt along the y direction is also adjusted to its zero tilt position for maximum retroreflective light coupling.

To realize the slope adjustor, one changes θ by providing in-plane tilt motion to FL that causes the incident beam to no longer strike the VBG at θ_c . Thus the separated diffracted beams across the spectrum no longer strike the DMDTM in a normal incidence mode, causing a θ -dependent linear beam shift of the different wavelengths returning to the FL. This varying physical translational beam shift on FL for each wavelength produces a changing attenuation (FL coupling) across the wavelength band. Specifically, the incident beam tilt around θ_c causes the returning beams at different wavelengths to translate in the DMDTM $+x$ direction to produce a positive slope while motion in the $-x$ direction produces a negative slope for wavelength-dependent attenuation. Changing θ for larger tilt angles around θ_c causes the received light to diverge due to longer path length propagation, thus causing the translational spread to increase at FL, producing increasing attenuation slope values. The θ_c position for FL ideally gives the gain slope adjustor's zero slope reference position as, in this case, all wavelengths returning to FL should be physically

(a)

(b)

Fig. 3 Measured example negative gain slopes of (a) -0.67 dB/nm and (b) -1.16 dB/nm from the hybrid spectral processor. Trace horizontal scale: 3-nm divisions; vertical scale: 10-dB divisions.

overlapping for complete and uniform power coupling into the fiber. Thus, combining analog tilt angle nanomotion of FL within the Fourier lens geometry and pinhole-type coupling of the FL, an analog-mode gain slope adjustor is realized within the Fig. 1 system. Do note that beam θ tilt motion due to FL in-plane tilt does move the WDM optical channels along the x direction on the DMDTM plane. Here the high mirror count and pixel density of the DMDTM becomes critical via the macropixel per channel concept as one simply reprograms the DMDTM mirrors to match the slightly shifted channel location. Another feature of the proposed processor is via analog tilt motion in the orthogonal y or non-Bragg direction that ideally gives a bias attenuation to the entire spectrum forming a broadband VOA. Finally, digital-mode per channel attenuation can be produced over channels in the entire spectrum via operations similar to the channelized digital equalizer described earlier and hence is not elaborated on in this paper.^{21,22}

3 Experimental Demonstration

As a first step, the Fig. 1 system is tested using an optical spectrum analyzer (OSA) internal broadband laser source and OSA observation setting from 1530 to 1560 nm. The VBG is aligned with the reference $\theta = \theta_c$ input beam for a $\lambda_c \sim 1545$ nm. Aligning all optics and mechanics, the

Fig. 4 (a)–(d) Measured example gain slopes with notches from the hybrid spectral processor. Trace horizontal scale: 3-nm divisions; vertical scale: 10-dB divisions.

present total fiber-in to fiber-out optical loss is ~ 12 dB indicated by the shown highest OSA trace levels versus reference levels in the experimental results. This loss at present is dominated by Fresnel losses of optics (as all optics are not antireflection coated for the 1550-nm band) and the unoptimal circulator (~ 2 dB) and fiber lens (~ 2 dB) losses. The DMDTM-based loss is a reasonable 1.9 dB, as the device is designed as a high diffraction efficiency blazed grating centered for the *C* band. Hence, with all optimal components, one can expect a 6-dB total optical loss.

By varying $\theta \leq \pm 2$ deg + θ_c , positive and negative gain slopes are generated, including the sample 0.67 and 1.16 dB/nm positive and negative slope adjustments shown in Fig. 2 and Fig. 3, respectively. Note here that ~ 1 dB of slope deviations are observed and these can be made smooth using some micromirrors from the DMDTM. Next, Fig. 4 shows sample simultaneous slope and notch controls using the high dynamic range channelized-based operation of the processor and FL tilt state controls. Specifically, notch depths in the 35-dB range can be reached as the DMDTM can provide its full 35-dB dynamic digital equalizer suppression, while the FL tilt control provides additional attenuation and slope adjustment. These basic early experiments show the expected powerful operations of the Fig. 1 processor. By tilting FL in the *y* direction, broadband spectrum attenuation is also realized, similar to the analog VOA operation. Present spectrum attenuation measurement dynamic range is limited to a -50 -dB relative range on the OSA due to the -50 -dB optical interport crosstalk level of the deployed circulator. Improved processor performance can be achieved using separate input and output fiber ports aligned along the *y* direction.

4 Conclusion

This paper demonstrated the basic principles of a novel microelectromechanical systems spectral processor for both spectral slope control and channel-based equalization. Im-

proved alignment and optimized optics is expected to improve processor experimental results such as loss, dynamic range, slope linearity, and $\theta = \theta_c$ state spectral flatness.

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