

All-fiber spectrum equalization filter with a reflection structure

Ying Zhang, MEMBER SPIE^A, Hon Luen Seck,^a
Yeng Chai Soh,^b and Zhao Gang Dong^a

^aSingapore Institute of Manufacturing Technology
71 Nanyang Avenue, Singapore 638075

^bNanyang Technological University
School of Electrical and Electronics Engineering
Nanyang Avenue, Singapore 639798

Abstract. We present an all-fiber spectrum equalization filter that uses a Mach-Zehnder interferometer terminated with a loop. Compared with existing results, the proposed filter has a simpler and a more efficient all-fiber structure for equalizing Gaussian-like spectra with desired specifications. © 2006 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2219096]

Subject terms: fiber optics; filters; spectrum equalization; broadband light sources.

Paper 050715LR received Sep. 7, 2005; revised manuscript received Jan. 7, 2006; accepted for publication Jan. 12, 2006; published online Jul. 20, 2006.

1 Introduction

Broadband light sources with flat spectra and high-power outputs are highly desirable in many applications where the light intensity of different wavelengths are of concerned.¹ With the advances in emitting materials, the use of light-emitting diodes (LEDs) with a proper fiber tapping-out structure provides a solution to achieve a high-power light output. However, the output spectra of these LEDs have a Gaussian shape. Therefore, equalization of the Gaussian spectrum of a LED becomes an important issue. Although many spectrum equalization techniques have been developed over the last years, most of them are for gain equalization of erbium-doped fiber amplifiers (EDFAs),^{2,3} and few are reported on design of a spectrum equalizer for a light source with Gaussian-like output spectrum. The difficulty lies in the fact that spectrum equalization for a light source requires not only a flat output spectrum but also a higher power output.

Recently, fiber lattice filters were proposed for equalizing Gaussian spectra and their performance has systematically analyzed.^{4,5} Although arbitrary flatness can be demonstrated theoretically with a lattice filter, a certain amount of input power is lost through the second output port of the lattice filter. This limits the power efficiency of the resultant light source. To overcome this problem, a fiber equalization filter with a feedback lattice structure is demonstrated with output power improvement of 3 dBm per wavelength and 0.5-dB ripple over 30 nm of bandwidth.⁶ As the filter requires two symmetric balanced Mach-Zehnder interferometers (MZIs) in the forward and feedback lattices, respectively, accurate control is required in the fabrication of the equal phase differential lengths and the symmetrical fiber coupling ratios. This creates difficulty when implementing

such a spectrum equalization filter. In this paper, we demonstrate a simple fiber equalization filter that is easy to fabricate while retaining the same merit equalization performance as the equalization filter with a feedback lattice structure.

2 Design of Equalization Filter with a Reflection Structure

The proposed spectrum equalization filter is formed by an all-fiber n 'th order MZI that is terminated by a loop, as shown in Fig. 1. The filter accepts the input light with a Gaussian-like spectrum at input port 1 through an isolator, and it outputs the equalized spectrum at port 2. The objective of the equalization filter design is to choose the $n+1$ fiber coupling ratios in the MZI such that the passband of the equalized spectrum is as flat as possible and its central power is as high as possible. To this end, we use the same design strategy as in previous results^{5,6} where the optimization of the central power incorporates the maximally flat conditions of an analytic function. We carry out the equalization filter design in the optical frequency domain characterized by $w = \Delta L \pi n_{\text{ref}} / \lambda$ where λ is the wavelength, n_{ref} is the refractive index of the optical fiber, and ΔL is the differential length of the MZI. In the optical domain, the input Gaussian-like spectrum is expressed by $F(w)$ and the power transmission of the equalizer from port 1 to port 2 is denoted as $P(w)$. Thus, after applying the equalization filter to the spectrum $F(w)$, the equalized spectrum is expressed by $P(w)F(w)$.

The design of a desired equalization filter is done in two steps. First, the Gaussian-like spectrum is approximated by an analytic Gaussian function $F(w) = \beta \cdot \exp[-(w - w_0)^2 / 2\delta^2]$, where w_0 corresponds to the central wavelength, β the amplitude, and δ the deviation of the Gaussian function. The approximation can be done in a least-squares sense when the measurement of the original Gaussian-like spectrum is available. Second, the fiber coupling ratios of the MZI are obtained by optimizing the central power of $P(w)F(w)$ at $w = w_0$ with constraints that specify the output spectrum to be as flat as possible in the neighborhood of w_0 . The constraints are obtained by applying the maximally flat conditions of the analytic function $P(w)F(w)$ at $w = w_0$. It is easy to verify that with the proposed filter structure, all the odd-order derivatives of the equalized spectrum $P(w)F(w)$ vanish at w_0 . Therefore, the maximal flatness of $P(w)F(w)$ is satisfied sufficiently by setting to zeros the highest possible number of even-order derivatives of $P(w)F(w)$ at $w = w_0$. Then, the equalization filter design is to obtain the appropriate fiber coupling ratios by solving a constrained optimization problem characterized by

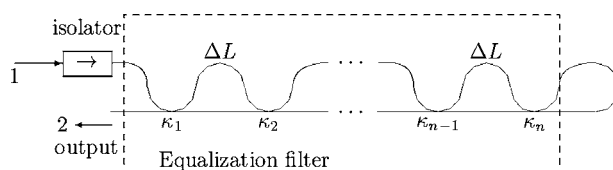


Fig. 1 Proposed equalization filter with the feedback structure.

Table 1 Central output power and the 0.5-dB bandwidth.

	Normalized central power c_0	Higher derivative c_1	Flatness order $2n+2$	0.5-dB bandwidth in wavelength
Proposed equalizer	0.69	-121.62	4	36 nm
Equalizer using feedback	0.71	-179.35	4	32 nm

$$\max_{\kappa_1, \kappa_2, \dots, \kappa_{n+1}} \{P(w_0)F(w_0)\}$$

subject to

$$[P(w)F(w)]^{(l)}|_{w=w_0} = 0 \quad \text{for } l = 2, 4, 6, \dots, 2n \quad (1)$$

where the superscript (l) denote the l 'th order derivative. Since the $2n+1$ 'th derivative of $P(w)F(w)$ automatically vanishes, $2n+2$ is the lowest order of the derivative of $P(w)F(w)$ at $w=w_0$ that does not equate zero. The number $2n+2$ is usually referred to as the order of the flatness. The constrained optimization problem given by Eq. (1) can be solved by using the Lagrange method. The derivations are tedious but similar to the procedures in previous literature,⁵ they are omitted here.

3 Performance of the Proposed Equalization Filter

The proposed spectrum equalizer is demonstrated by comparing its performance with that of the spectrum equalization filter using a feedback lattice structure.⁶ First, we examine the central output power and the bandwidth of a given flatness, which are two important specifications for spectrum equalization. Taking advantage of the maximally flat principle, the resultant equalized spectrum can be approximated around the central wavelength by a polynomial $G(w) = c_0 + c_1 w^{2n+2}$ where c_0 is the central power $P(w_0)F(w_0)$ and c_1 is the $2n+2$ 'th derivative of $P(w)F(w)$

at $w=w_0$. Then, the bandwidth of the equalized spectrum can be evaluated by the ϵ -dB bandwidth where ϵ is a small value that can be specified by the users. It is defined as the distance between the two points where the equalized spectrum intersects the line with a power of ϵ -dB level less than the maximal output power. Using the polynomial approximation, the ϵ -dB bandwidth is obtained as $w_b = 2[c_0(1 - 10^{-\epsilon/10})/c_1]^{1/(2n+2)}$ in the optical frequency domain and $BW_\epsilon = 2(\lambda_b - \lambda_c) = 2[\lambda_c \Delta L \pi n_{ref} / (\Delta L \pi n_{ref} - 2w_b \lambda_c) - \lambda_c]$ in the wavelength domain where λ_c is the central wavelength of the Gaussian spectrum to be equalized and it is used to convert the spectrum from the wavelength domain to the optical frequency domain.

To compare the performance of the proposed equalization filter and the equalization filter with a feedback lattice structure, we consider the equalization of a Gaussian-like spectrum in Fig. 2 to have a fourth order flatness that requires $n=1$. The spectrum is that of a superluminescent LED (SLED). It is also used in subsequent experiments. Using a least-square method, the spectrum can be approximated by choosing $\delta=0.638$ and $w_0=1533.8$ nm. Thus, we take $\Delta L=18.5$ μm so that the central wavelength of the equalization filter sits at 1533.8 nm. For $n=1$, the equalization filter is a first-order MZI consisting of two couplers. Since all odd-order derivatives of $P(w)F(w)$ resulting from the proposed equalizer vanish at $w=w_0$, it suffices to force $[P(w)F(w)]^{(2)}=0$ at $w=w_0$ to achieve the fourth order flatness. Applying the proposed design, the desired fiber coupling ratios of the MZI are $\kappa_1=0.74$ and $\kappa_3=0.74$, respectively. The central output power and the 0.5-dB bandwidth of the equalized spectrum are calculated and listed in Table 1 where the corresponding results obtained by using the equalization filter with a feedback lattice structure are also given for comparison. The data show that the two equalization filters can achieve the same equalization results. However, it is noted that the previous equalization filter with a feedback lattice structure has to use two second-order MZIs consisting of six symmetric fiber couplers to achieve the same order of flatness. Therefore, the current proposed equalization filter has improved the efficiency of using fiber filter to equalize a Gaussian-like spectrum.

Next we examine the experimental performance of using the proposed equalizer to equalize the SLED spectrum as shown in Fig. 2. The equalization filter designed above is fabricated using the same technique as in previous literature.^{5,6} After the MZI is fabricated, one of its ends is fused to form the loop. Connecting the filter to the output of the SLED with the Gaussian-like spectrum, the equalized spectrum is measured on OSA and it is shown in Fig. 2. For comparison, an equalization filter with a feedback lattice structure is also fabricated. Its equalization spectrum is

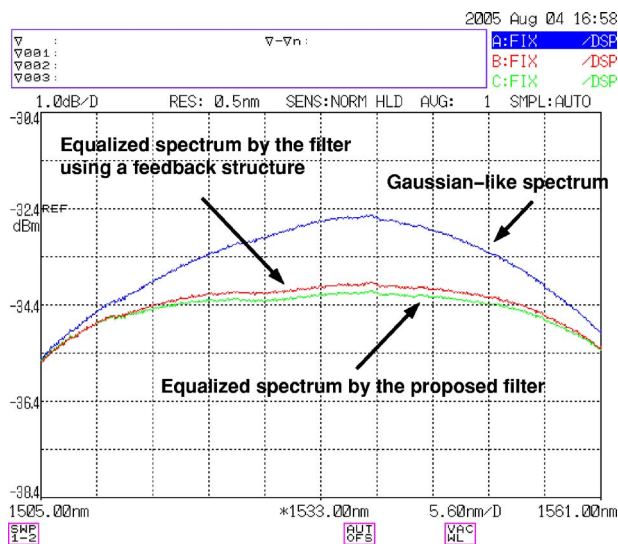


Fig. 2 Experiment results of equalizing a Gaussian-like SLED spectrum.

measured and recorded in Fig. 2. It is shown that the proposed equalization filter can equalize the SLED spectrum with 0.5-dB ripples over a 30-nm bandwidth. This result is similar to that of the equalizer using a feedback lattice structure. But the proposed equalization filter is clearly simpler and it has an easy-to-control fabrication procedure, while the equalizer with a feedback lattice structure requires accurate control of the fabrication of six fiber couplers to achieve the symmetric feedback. The experimental results demonstrate the efficiency of the proposed equalizer.

Acknowledgments

This paper is supported by SIMTech U04-P-106B.

References

1. G. Keiser, *Optical Fibre Communications*, 3rd ed., McGraw-Hill, New York (2000).
2. Y. P. Li, C. H. Henry, E. J. Laskowski, C. Y. Mak, H. H. Yaffe, and R. Sweatt, "A waveguide EDFA gain equalization filter," *Electron. Lett.* **31**, 2005–2006 (1996).
3. B. J. Offrein, F. Horst, G. L. Bona, R. Germann, H. W. M. Salemink, and R. Beyeler, "Adaptive gain equalizer in high-index-contrast SiON technology," *IEEE Photonics Technol. Lett.* **12**, 504–506 (2000).
4. Q. J. Wang, Y. Zhang, and Y. C. Soh, "Design of spectrum equalization filter for SLED light source," *Opt. Commun.* **229**, 223–231 (2003).
5. Y. Zhang, Q. J. Wang, and Y. C. Soh, "Equalization of Gaussian-like spectrums with optical lattice filters," *J. Opt. Soc. Am. B* **22**(7), 1498–1511 (2005).
6. Z. Dong, Y. Zhang, Q. J. Wang, and Y. C. Soh, "Gaussian-like spectrum equalization using an all-fiber lattice filter with symmetric Feedback structure," *Opt. Eng.* **44**, 050504 (2005).