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A simultaneous wavelength tuning and stabilization scheme of a fiber-optic interferometer filter

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We successfully demonstrated a stabilized fiber-optic Mach-Zehnder interferometer filter with continuous tunability. The tunable scheme was achieved with fine wavelength control of an 1.3 μm tunable laser diode used as a stabilization light source. The transmission wavelength of the tunable filter was shifted linearly with respect to the wavelength change of the stabilization light source.

I. INTRODUCTION

Wavelength Division Multiplexing (WDM) communication systems, which are known to be promising ways to achieve a few Tb/s of transmission capacity, inevitably require many devices to manipulate light signals in the wavelength domain [1]. Much research effort has been devoted to optical interferometer filters for potential applications in useful WDM devices such as a WDM channel divider [2], a multiplexer (Muxer), and demultiplexer (Demuxer) [3,4,6]. However, since the fiber interferometers are usually very sensitive to environmental perturbations, they have to be stabilized in order to be used as practical devices [5]. We have successfully demonstrated a fiber-optic Mach-Zehnder interferometer (MZI) filter stabilized with an active phase tracking (APT) method using a separate stabilization light source of a 1.3 μm laser diode whose lasing wavelength is different from the 1.5 μm signal wavelength to be filtered [6]. Our stabilized MZI filter has two important advantages of long term stability and usefulness for both discrete and broadband input spectra. However, it still has a difficulty in continuous tuning of its transmission wavelengths. Since the transmission peak wavelengths and their intervals for an MZI filter are mainly determined by the OPD, we can in principle change the transmission wavelengths continuously by precise elongation of each fiber arm of the MZI. However, continuous tuning of transmission wavelengths by that approach is impossible in our previous stabilization scheme, because the intentional elongation to change the OPD is also compensated by the stabilization scheme, and as a result, the OPD can not be changed. The OPD is fixed independent of the elongation as long as the elongation does not exceed the compensation range of the stabilization scheme. Therefore, only discrete tuning is possible in the previous stabilization scheme, whose tuning step corresponds to the width of the compensation range of the stabilization electronics. In this letter, we report, for the first time to our knowledge, a continuously tunable multi-wavelength transmission filter based on a stabilized fiber-optic MZI by changing the wavelength of the stabilization light source.

II. PRINCIPLE

Figure 1 shows an experimental setup for the demonstration of a transmission wavelength-tunable stabilized fiber-optic MZI filter. When a broadband optical source of $I_0(\lambda)$ is launched into the input port, the output spectrum from the interferometer filter is described as follows:

$$I(\lambda) = \frac{I_0(\lambda)}{2}\left\{1 \pm \cos\left(\frac{2\pi n(\lambda)\Delta l}{\lambda}\right)\right\} \tag{1}$$

where $n(\lambda)$ and Δl are the refractive index of the fiber core and the fiber length difference of the interferometer's two arms, respectively. If the MZI is successfully stabilized by the APT scheme using a stabilization light source with a wavelength of λ_s, the phase difference of the interferometer is held at a quadrature phase as follows:

$$\frac{2\pi n(\lambda_s)\Delta l}{\lambda_s} = \left(2m + \frac{1}{2}\right)\pi, \tag{2}$$

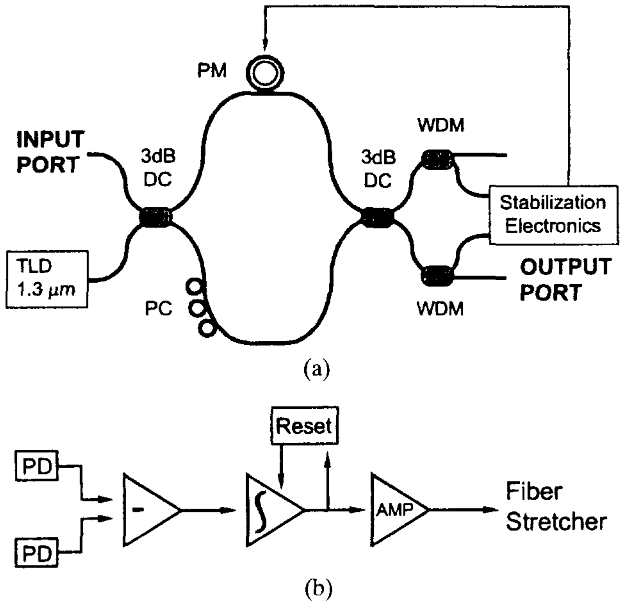

FIG. 1. (a) Experimental setup for the transmission wavelength tunable fiber-optic MZI filter. TLD : tunable laser diode, DC : directional coupler, PM : phase modulator, PC : polarization controller, WDM : wavelength division multiplexing fiber coupler. (b) Schematic of the stabilization electronics.

where $n(\lambda_s)$ is the refractive index of the fiber core at the stabilization wavelength, and m is an integer. If Δl obtained from equation (2) is substituted in equation (1), the output spectra can be rewritten as a function of the stabilization light λ_s:

$$I(\lambda) = \frac{I_0(\lambda)}{2}\left[1 \pm \cos\left\{\frac{n(\lambda)\lambda_s(2m+\frac{1}{2})\pi}{n(\lambda_s)\lambda}\right\}\right]. \quad (3)$$

The wavelength of the stabilization light source affects the phase term of the cosine function in the output spectra. Consequently, the transmission peaks of the stabilized MZI filter can be continuously tuned by changing λ_s precisely. For example, as the wavelength of the stabilization light source increases, the phase of the cosine term increases, and the transmission peaks of the interferometer filter move toward the long wavelength region.

III. EXPERIMENTAL RESULTS

Figure 1(a) shows an experimental setup of a transmission wavelength-tunable stabilized fiber-optic MZI filter which was optimised to optical signals of 1.5 μm wavelength band. The MZI consisted of single-mode communication fibers, two 3 dB directional couplers (DC's), a phase modulator (PM), and a polarization controller (PC). Total fiber length of each arm was about 15 m, and the OPD of the MZI was about 1.5 mm. The stabilization scheme consisted of a tunable laser diode (TLD) of 1.3 μm wavelength emission band for the stabilization light source, two WDM couplers for separating the 1.3 μm light and the 1.5 μm signals, and stabilization electronics whose schematic is shown in figure 1 (b). The stabilization scheme was based on controlling one arm length of the MZI against environmental perturbations with an electronically feedbacked fiber stretcher. The fiber stretcher was composed of lengths of fiber wrapped around a PZT tube, and provided a conversion ratio ofabout π rad/voltage at modulation frequencies below a few kHz.

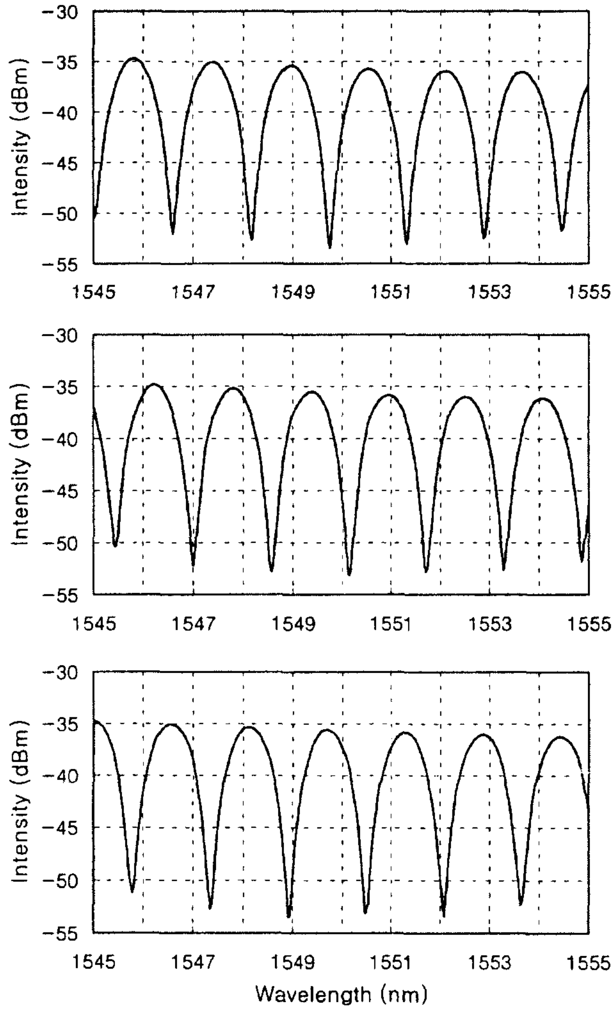

FIG. 2. Three transmission spectra of the MZI filter showing the wavelength shift of the transmission peaks for three different stabilization wavelengths of 1312.22, 1312.56, and 1312.84 nm from the top trace to the bottom one.

In order to demonstrate the proposed scheme for continuous transmission wavelength tuning of a stabilized MZI filter, a TLD was used in our experiment as a stabilization light source capable of precise wavelength tuning. Optical power of the TLD was about 300 μW. Figure 2 shows output spectra of the MZI fil-

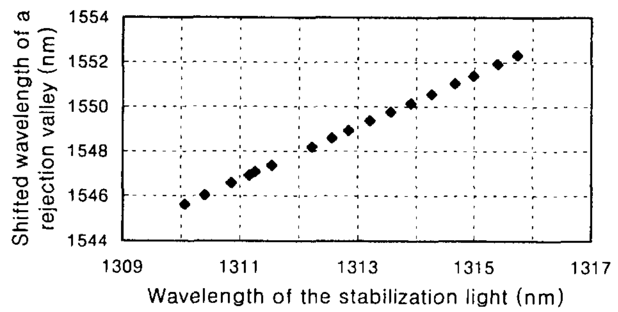

FIG. 3. Measured wavelength shift of the filter's rejection valley as a function of wavelength of the stabilization light.

ter when amplified spontaneous emission (ASE) of an EDFA was launched into the filter through the input port. The wavelengths of the stabilization light source were adjusted at 1312.22, 1312.56 and 1312.84 nm from the top figure to the bottom one, respectively. The transmission period is about 1.6 nm corresponding to the OPD of 1.5mm. It is clearly seen from the spectra in figure 2 that transmission or rejection wavelengths move according to the wavelength variation of the stabilization light source. As the wavelength of the TLD increases, the transmission peaks move toward a long wavelength region, as expected from the cosine term of the equation (3). We monitored a rejection wavelength instead of a transmission one for convenient measurement of its movement when the wavelength of the TLD increased from 1310 nm to 1316 nm. Figure 3 plots the measured wavelength variation of the rejection valley at 1549 nm shown in the bottom figure of figure 2 with change of the stabilization wavelength. The rejection wavelength varies linearly with the wavelength of the TLD with a slope of about 1.18. The relation between wavelength shift of rejection valley $\delta\lambda$ and wavelength variation of stabilization light $\delta\lambda_s$ can be deduced from a simple theoretical study as follows:

$$\delta\lambda = \frac{\lambda}{\lambda_s}\frac{n(\lambda_s)}{n(\lambda)}\delta\lambda_s. \quad (4)$$

The slope can be approximated to the wavelength ratio λ/λ_s because the refractive index ratio $n(\lambda_s)/n(\lambda)$ is almost 1. For our experiment where the transmission signal band was around 1.55 μm and stabilization light band was around 1.312 μm, the wavelength ratio i.e. the slope is calculated to be about 1.18, which agrees well with the measured value. Therefore, continuous wavelength tuning of the transmission peaks of the stabilized MZI filter can be possible with precision determined by the tunability of the wavelength of the stabilization light. It is obvious that the stability of this type of stabilization scheme depends on that of the stabilization light source. The wavelength of the TLD varied very slowly within 0.05 nm during one day. This fluctuation seemed to be a major factor affecting overall transmission wavelength variation of less than 0.1 nm. The overall tuning range of the transmission wavelength is also strongly dependent on that of the stabilization light. No change of the transmission period due to the change of the stabilization wavelength was observed during the monitoring. One factor indicating the performance of the optical filters is an extinction ratio defined as the ratio of intensity of the transmission peaks to that of the rejection valleys. The extinction ratio of the MZI filter was strongly dependent on the scalar product of the polarization states of the two interfering beams. We could easily get an extinction ratio of about 15 dB as shown in figure 2 with an appropriate adjustment of the PC. Even though we used a TLD as stabilization light source in order to demonstrate the proposed smultaneous wavelength tuning and stabilization scheme of a fiber-optic MZI filter, other effective sources than the TLD make the scheme more practical.

IV. CONCLUSIONS

We have described a successful demonstration of a stabilized MZI filter capable of continuous tuning of its transmission wavelength by varying the wavelength of a 1.3 μm tunable laser diode utilized as the stabilization source. The transmission wavelength of the tunable filter was shifted linearly along with the wavelength change of the stabilization light source with a slope whose magnitude was equal to the wavelength ratio of the filtered signal to the stabilization light. This wavelength-tunable interferometer filter can be useful for various WDM filter applications, such as multi-wavelength light generation, Muxer/Demuxer, and gain flattening of an EDFA.

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