Wavelength-sensitive Thin Film Filter-based Variable Fiber-optic Attenuator with an Embedded Monitoring Port

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Abstract - A wavelength-sensitive three-port variable fiber-optic attenuator (VFOA) is introduced by incorporating the movable optical mirror with a fixed desired thin film filter. Experimental proof of concept using an off-the-shelf measured 1545.60 nm thin film filter and a mechanically movable mirror shows a low 0.47 dB optical loss, a low polarization dependent loss of 0.6 dB at maximum optical attenuation setting, and a 15.9 dB dynamic range measured at the output port. Several proposed wavelength-sensitive three-port VFOAs can also be cascaded to form a low cost compact multiwavelength amplitude controller.

Key Words - Variable optical attenuators, Fiber-optic attenuators, Thin film filters, Wavelength division multiplexing.

1. Introduction

The variable fiber-optic attenuator (VFOA) is a basic building block for several optical systems such as wavelength division multiplexed (WDM) transmission systems, optical beam formers, and fiber-optic adaptive controls. Various types of VFOAs have been reported in the past including the use of polymer-based thermo-optical approach that provides only two ports with a 4 dB wavelength dependent attenuation over a 50 nm optical bandwidth [1]. Another two-port VFOA module is implemented by using liquid crystal (LC) technology [2]. However, the LC-based VFOA requires polarization diversity technique for achieving low polarization dependent loss (PDL), although it is a no moving part moderate response speed VFOA, thus adding the cost to the VFOA module. Another technology that can be used to build the VFOA is microelectromechanical systems (MEMS). Although MEMS-based VFOAs [3-4] can be made compact, consume less electrical power, and have moderate response speed, they need an expensive hermetically sealed packaging. In addition, when one wants to independently control the amplitude of N wavelength optical beams in WDM transmission systems, N VFOA modules are inserted between the WDM demultiplexer and multiplexer. Furthermore, if two-port VFOAs are deployed, N fiber-optic taps are typically needed for accurate closed loop control, implying a high cost and complicated WDM amplitude control system. Hence, it would be highly desirable to have a high wavelength sensitive three-port VFOA module in which one port is used as the input port while the two remaining ports function as the output and the monitoring terminals, respectively. In this way, by cascading N wavelength-sensitive three-port VFOAs together, a simple WDM amplitude control system can be formed as shown in Fig.1. The closed loop control system can be done by feeding all electrical currents converted from the wavelength-sensitive three-port VFOA array to the electronic control box and connecting the control bus between them. This kind of arrangement can also be employed in optical performance monitoring systems.

Today, one reliable basic optical component that can be used to build such a required wavelength dependent fiber-optic module is the thin film filter (TF). The TF is an important component for realization of static fiber-optic 1x2 [5] and 2x2 add/drop switches used in current WDM systems. Very recently, we have also shown that a reconfigurable WDM 2x2 fiber-optic switch can be realized by independently controlling the positions of the TF and the optical mirror via the use of two mechanical actuators, leading to ease of free

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space optical alignment and control [6]. In addition, this same basic design concept has been recently employed in our wavelength sensitive three-port VFOA [7]. However, taking into account the packaging requirement and the controlling ability, it would be desirable that the VFOA module has as less component as possible so that the cost and packaging specification can be made optimally. Hence, in this paper, we propose and experimentally demonstrate a high wavelength-sensitive TF-based VFOA by using only one mechanically movable mirror. Our key idea is to fix the desired TF near the dual fiber-optic collimator and to control the position of the mirror located between the TF and the single fiber-optic collimator.

2. Proposed Structure

Fig.2 shows our proposed wavelength-sensitive TF-based three-port VFOA module for controlling the amplitude of the desired wavelength (e.g., λ_1) optical beam. It consists of a dual fiber-optic collimator, a fixed TF element, a programmable optical mirror sat on the mechanical actuator, and a single fiber-optic collimator. At the terminal end of the single fiber-optic collimator, a photodetector (PD) can be connected as shown in Fig.1 for monitoring the optical power level. In addition, because in this structure, only the mirror is moved into and out of the optical path, the speed of our VFOA is equivalent to the response time of typical mechanically controlled VFOAs and optical switches available in the market. The operation of our proposed WDM TF-based three-port VFOA can be described as follows. The multiwavelength optical beam from the IN port emanates from the graded index (GRIN) lens of the dual fiber-optic collimator. When the mirror is programmed to be out of the optical path, the desired λ_1 optical beam passes through the TF and is coupled into the single fiber-optic collimator, implying that the electrical current generated by the PD located at the end of this fiber-optic collimator for the λ_1 optical beam is at the maximum level. In other words, there is no λ_1 optical beam at the OUT port, indicating a maximum optical attenuation. In the meantime, the remaining wavelength optical beams are reflected from the TF to the OUT port with low optical loss values.

On the other hand, when the mirror is set to move into the optical path and completely covers the cross-sectional area of the incident optical beam, the λ_1 optical beam passing through the TF is reflected at the mirror back to the OUT port, leading to a minimum optical attenuation. At this operation, other remaining wavelength optical beams emerging from the GRIN lens are also sent to the OUT port via reflection from the TF. As a result, there is no λ_1 optical beam incident on the PD and the electrical current generated by the PD is minimal. Based on these two operations, we can see that the desired optical attenuation level for the λ_1 optical beam at the OUT port can be easily accomplished by controlling the position of the mirror in the analog fashion. Note that if the mirror has binary operation, our proposed wavelength sensitive TF-based VFOA forms a reconfigurable 1x2 fiber-optic add/drop switch. By assuming that at the beginning the mirror is completely in the optical path and the optical beam amplitude emanating from the GRIN lens has a Gaussian profile, the normalized optical power for the λ_1 optical beam at the OUT port can be written as.

$$P_o = 1 - erf(\sqrt{2}x/w), \qquad (1)$$

where erf(c) is the error function of c, x is the position of the mirror, and w is a 1/exp(2) optical beam radius at the mirror plane. Similarly, the normalized optical power at the monitoring port for the λ_1 optical beam can be expressed as.

$$P_m = erf(\sqrt{2}x/w). \qquad (2)$$

From eqns(1)-(2), the optical attenuation value in the unit of decibels is equal to $-10\log(P)$, where P is set to P_o and P_m for calculating the optical attenuation at the OUT and the monitoring ports, respectively.

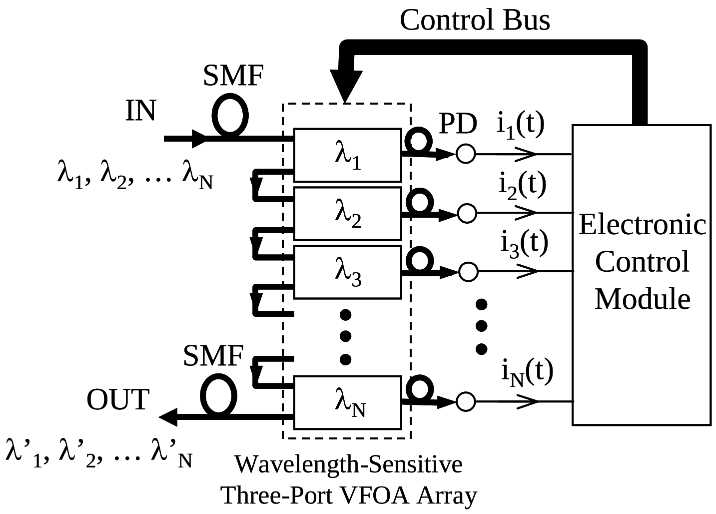


Figure 1. WDM amplitude controller with feedback control system using an array of wavelength-sensitive three-port VFOAs. SMF: Single-mode optical fiber, PD: Photodetector.

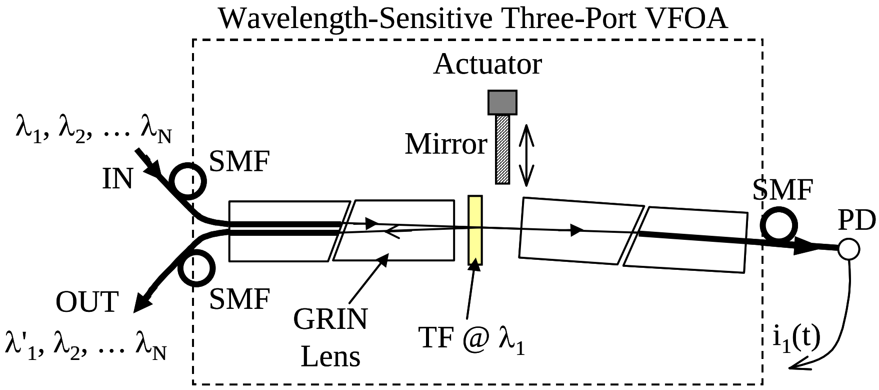


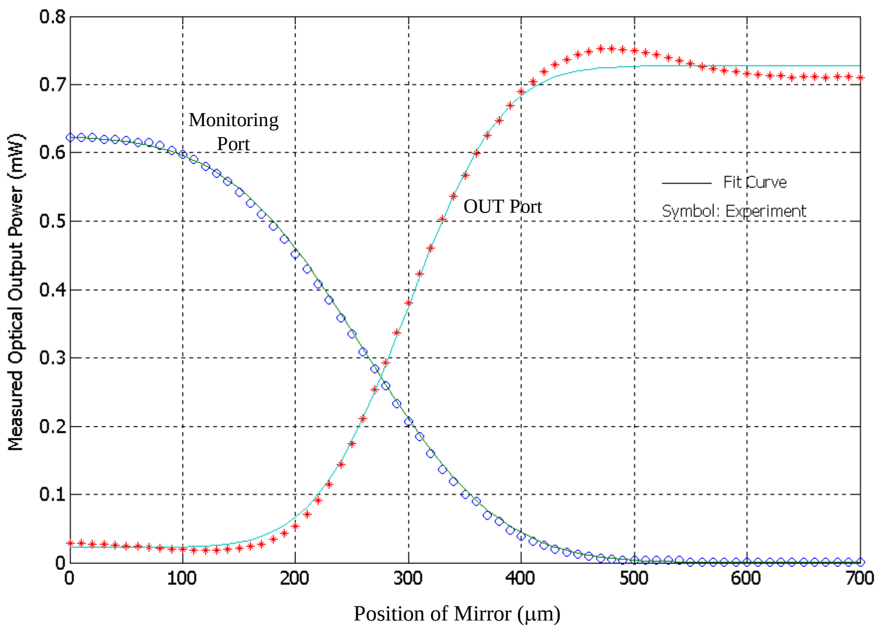
Figure 2. Our proposed wavelength-sensitive three-port TF-based VFOA structure designed at λ_1.

3. Experimental Demonstration

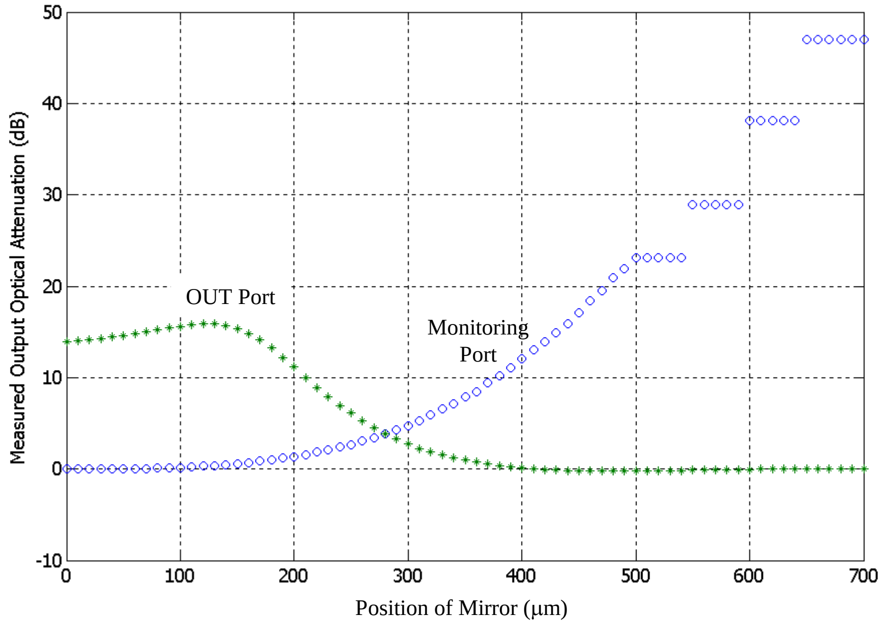
Based on the optical components available in our laboratory, we set up the experiment according to Fig.2. The mirror is a 1-mm-thick glass slide having a 50-nm gold layer on top of a 2-nm chromium layer coated on one side. It is positioned behind the TF and is controlled to move in and out of the optical path by a hand-operated mechanical translation stage. The TF is first positioned and aligned in the optical path by using another hand-operated mechanical translation stage and then fixed at the focal plane of the dual fiber-optic collimator. The TF is a commercially available 1.4x1.4 mm^2 four-cavity dense WDM filter, and its designed center wavelength is 1546.12 nm with a 25-dB stopband of 1 nm. However, after aligning the TF in the structure, the measured center wavelength is shifted to 1545.60 nm (λ_0). The tunable light source from Santec Inc. is directly connected to the IN port via FC/APC adapter, and the wavelength interval is set to 1 nm. The measured free-space optical path is 4 mm which is near the designed 5-mm working distance of the fiber-optic collimators in order to optimize the free space coupling efficiency. The output end of the single fiber-optic collimator is then connected to the PD via FC/APC adapter.

One important parameter for the VFOA is the optical loss. Measured low optical losses of 0.47 dB and 1.04 dB are investigated at the OUT and monitoring ports, respectively, when the mirror is out of the optical path. The difference in optical loss comes from the free space coupling efficiency between the fiber-optic collimators. Another important component issue is the dynamic range of our wavelength-sensitive TF-based three-port VFOA. By moving the mirror out of the optical path in a 10-μm step, the optical powers at the OUT and the monitoring ports are investigated as shown in Fig.3(a), indicating that our experimental result agrees well with our theoretical analysis. In this case, the undershoot and overshoot of the measured optical power are due to the diffraction at the edge of the mirror when it is near the two tailing edges of the Gaussian optical beam. The optical attenuation values for both ports are also plotted as shown in Fig.3(b), pointing out a high dynamic range of 47 dB at the monitoring port and a 15.9 dB dynamic range at the OUT port. Note that the discrete change in measured optical attenuation at the monitoring port when the mirror position is > 500 m is due to a very small change in optical power level between mirror position settings.

Optical isolation of the optical beam outside the center wavelength is also an important issue for our wavelength-sensitive TF-based three-port VFOA. It is defined as the ratio between the measured input optical power and the measured optical power at the unwanted port. At the monitoring port, the measured optical isolations manifested in Fig.4(a) are better than 47 dB and 25 dB when the mirror is in and out of the optical path, respectively. For the OUT port, a 15.9 dB optical isolation is obtained as shown in Fig.4(b). These results also verify that only the λ_0 wavelength optical beam is attenuated by controlling the position of the mirror in the optical path. In addition, as shown in Fig.4(b), because the mirror is not at the focal plane of the dual fiber-optic collimator, the optical loss of λ_0 optical beam reflected from the mirror is adjusted to make it equal to optical losses of other wavelength channels by playing with the mirror position along the optical axis. At the λ_0 operating wavelength, the PDLs of 0.04 and 0.6 dB are also measured at the monitoring and the OUT ports, respectively, when the mirror is not in the optical path. When the mirror is set to be in the optical path, a measured low PDL of < 0.03 dB is obtained. Higher VFOA performance can be achieved by using higher quality mirror and TF.

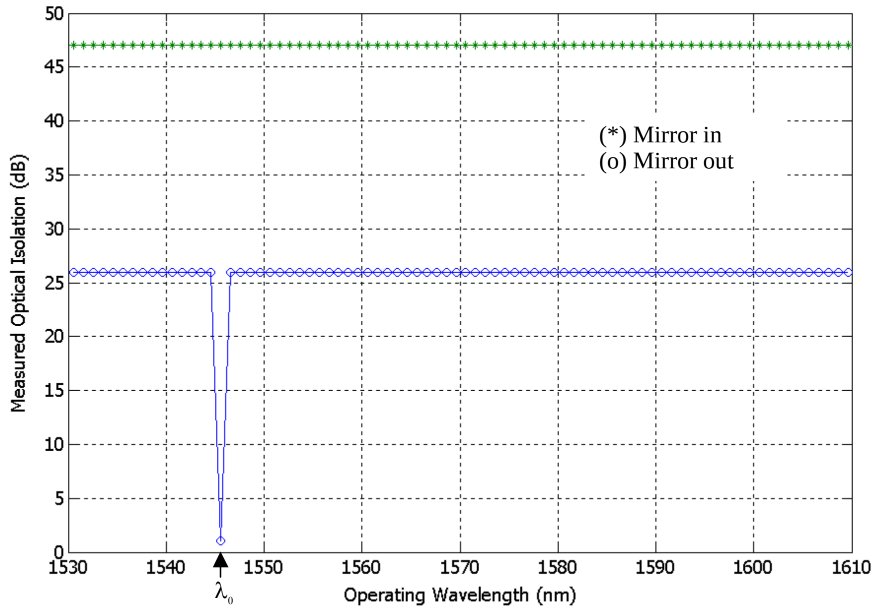


(a)

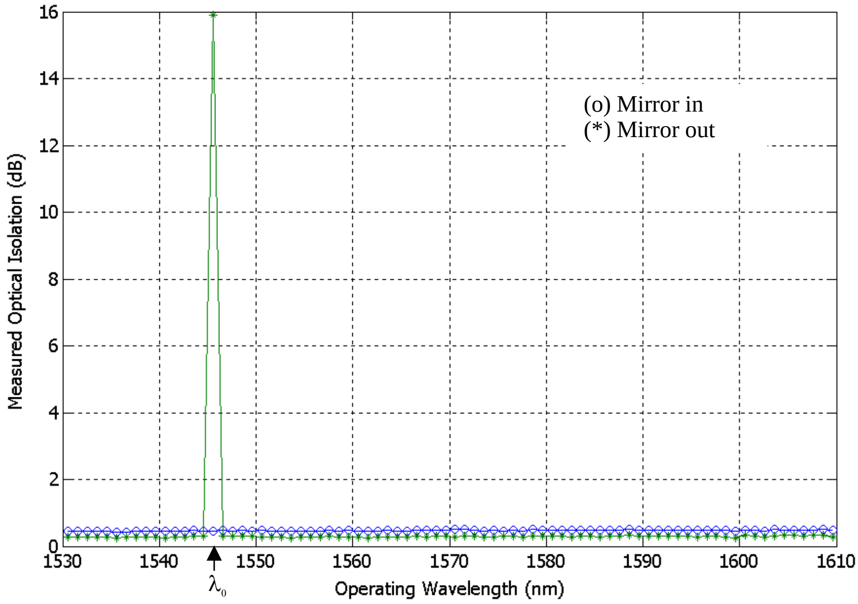


(b)

Figure 3. (a) Measured optical output power and (b) measured optical attenuation at λ_0.



(a)



(b)

Figure 4. Measured optical isolation over a 80-nm operating wavelength at the (a) monitoring port and (b) OUT port.

4. Conclusion

In this letter, we propose and experimentally demonstrate a wavelength-sensitive TF-based VFOA with an embedded monitoring port. Our VFOA key idea is to fix the desired TF near the dual fiber-optic collimator and to use the movable mirror located between the TF and the single fiber-optic collimator. This proposed TF-based three-port VFOA can be used to realize a low-cost large-channel-count amplitude control system. Our experimental proof of concept at the center operating wavelength shows a 15.9 dB dynamic range at the OUT port and a 47 dB maximum optical attenuation at the monitoring port. Low optical loss and PDL values of 0.47 dB and 0.6 dB are also measured at the OUT port. Limitations in our VFOA performance can be overcome by utilizing higher quality mirror and TF.

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