Electronic Feedback System for Stabilization of Fiber Ring Resonator

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We propose a simple technique to stabilize the optical output intensity of a fiber ring resonator. The electronic feedback circuit system, which consists of two voltage control oscillators, a phase comparator, and a low pass filter, is applied to the fiber ring resonator in order to compensate the optical phase shift in the ring loop. The reference electrical signal determines the operating condition of the fiber ring resonator for the desired optical output signal. The experimental results within the operating range agree well with the analytical results. The simulated performance of the proposed model is also compared with that of other existing models and shows significant improvement over them.

Keywords: Stabilization, fiber ring resonator, electronic feedback circuit, drift effect.

I. Introduction

Optical components and devices play an important role in maximizing the speed of all-optical system applications, such as optical communication and optical signal processing. The use of fiber ring resonators is an attractive approach that has been demonstrated in many optical devices, including multiplexers/demultiplexers, optical filters, fiber lasers, and analog-to-digital (A/D) converters [1]-[10]. This is due to the simple structure and characteristics of the fiber ring resonator. One technique to achieve all-optical/in-fiber devices employs the concept of imitating the characteristics of electronic components with optical ones. For example, the idea of imitating electronic devices by means of acousto-optic devices, such as phase modulators, microwave frequency decoders, and photonic switching and wavelength selector/multiplexers, has been theoretically proposed and investigated [11]-[14]. Although most of those devices include the simple structure of a fiber ring resonator, the practical demonstration of such devices is not easy to accomplish due to the high sensitivity to the environment of the fiber ring resonator. To reduce the sensitivity or the drift effect of the ring resonator, the random optical phase shift in the ring caused by the environment needs to be compensated. So far, the compensation of the optical phase shift in the fiber ring resonator has been experimentally demonstrated using the composition of electronic circuits for the purpose of fiber-loop-length stabilization [15]-[17]. Studies show that the error signal, which is used to stabilize the ring resonator and results from the comparison between the reference signal and the output signal of ring resonator, may have high error due to additive white Gaussian noise (AWGN) [15]-[17]. Thus, the error effect from AWGN in terms of amplitude comparison between the two signals is high. That is,

the error signal has high fluctuation [18], [19]. In 1993, Reynaud and others [20] proposed another method to stabilize the output intensity of the fiber ring resonator by using the servo control system. A servo loop consists of a packet identifier (PID) filter and driving electronics to actuate an optical fiber stretcher. The stabilizing signal of this method is generated from the amplitude comparison between error signal and triangular waveform. However, AWGN can still affect the system performance. In 1998 and 2001, Coen and others proposed a method to stabilize the output intensity of a nonlinear fiber ring resonator by using the nonlinear dynamic of a synchronously pumped all-fiber ring cavity [21], [22]. This method offers high accuracy but it is impractical for a linear operating fiber ring resonator.

In this study, we have further developed a simple technique of employing an electronic feedback circuit to stabilize the optical output signal of the fiber ring resonator [23]. Although the concept is similar to previous works [15]-[17], the principle of circuit operation is different, and the stabilization is improved. The proposed electronic feedback circuit is composed of two voltage control oscillators (VCOs), a phase comparator (PH), and a low-pass filter (loop filter). The drive electrical signal of the piezoelectric fiber stretcher (PZT), which stabilizes the output signal of the fiber ring resonator, is generated from the frequency comparison of two signals produced by VCO1 and VCO2. The advantage of this method is that it is robust to AWGN because the signals are compared in terms of their frequencies rather than amplitude. The characteristics of the proposed electronic feedback circuit in terms of the relationship between reference voltage and the output signal of the fiber ring resonator as well as its design criteria are also theoretically investigated.

II. Concept Theory

To explain the operating principles of the proposed system, the characteristics of an ordinary optical fiber ring resonator will be recalled from [24]. Figure 1 shows the basic configuration and the transfer function (normalized output intensity) of an optical fiber ring resonator formed by a single-mode directional optical coupler with a closed loop ring. When an optical input signal with intensity I_1 is launched into port 1 of the optical coupler, its intensity is split into the output signal I_3 and the feedback signal I_4. The feedback signal travels within the ring and becomes another input signal I_2 to the coupler. Here, a is the intensity splice loss in the ring, α is the fiber loss per unit length, L is the fiber loop length, β is the optical wave number, γ is the coupler insertion loss, and k is the intensity coupling coefficient of the coupler defined by $k = \left| E_4/E_1 \right|^2 = I_4/I_1$, where E_i and I_i are the electric field and
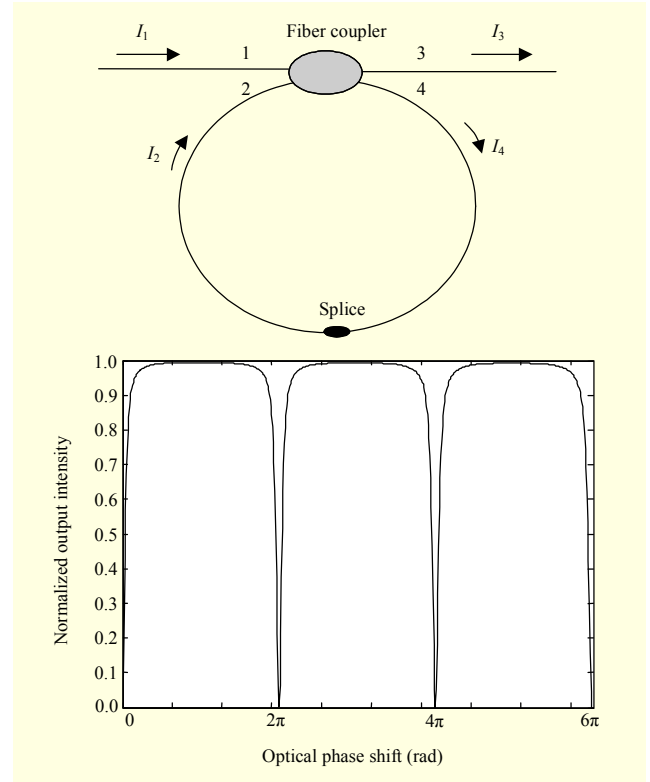

Fig. 1. Fiber ring resonator and its normalized output intensity.

the optical intensity, respectively, at the i-th port. The output intensity I_3 as a function of the input intensity I_1, omitting the time variation $\exp j\omega t$, can be expressed as

$$I_3 = (1-\gamma)\left[1 - \frac{k(1-k-\Theta)}{(1-k)(1+\Theta-2\sqrt{\Theta}\cos\phi)} \right] \cdot I_1, \quad (1)$$

where $\Theta = (1-k)(1-a)(1-\gamma)e^{-2\alpha L}$, and $\phi=BL$, in which $\beta = n\omega/c = 2\pi n/\lambda$, where n is the fiber core index, ω is the optical angular frequency, λ is the optical wavelength, and c is the velocity of light in free space. Note that ϕ is the optical phase in the ring with an optical path length equal to the loop length. Figure 1 shows the normalized output intensity I_3 of the fiber ring resonator as a function of optical phase shift. Since the output intensity depends on the optical phase in the loop, it can be seen at the resonant condition that I_3 is minimal when $\beta L = 2(m-1)\pi$, where m is the integer. At this resonance, most energy will be trapped in the fiber loop because the light coupling from port 1 to port 4 constructively interferes with the light coupling from port 2 to port 4. Similarly, destructive interference takes place between coherent light entering port 3 from port 1 and port 2. In practice, the fiber ring resonator is very sensitive to the environment, and this causes a variation (drift effect) of the optical phase ϕ. Consequently, the output intensity I_3 becomes unstable. Since ϕ is directly related to the
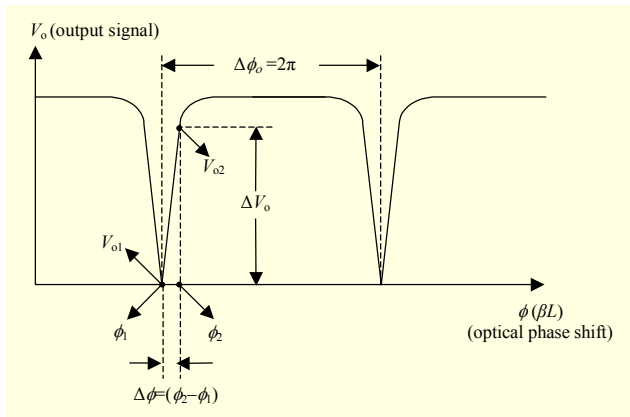
Fig. 2. Relationship between the output signal and optical phase shift.

Fig. 3. Configuration of the stabilization of the fiber ring resonator.

variation of the fiber loop length L, the variation of the optical phase $\Delta\phi$ can be given by

$$\Delta\phi = \beta\Delta L = \frac{2\pi n}{\lambda}\Delta L, \qquad (2)$$

where ΔL is a variation of fiber loop length.

Figure 2 shows the relationship between the output intensity I_3 normalized by means of the electrical output signal (V_o) of the fiber ring resonator and the optical phase shift (ϕ). It is clearly seen that a small phase shift in the vicinity of the resonance can result in a lot of intensity change at the output (drift effect). In practice, this sensitivity is simply caused by the environmental condition, which is not stable. As seen in the figure, when the optical phase varies from ϕ_1 to ϕ_2 ($\Delta\phi = \phi_2 - \phi_1$), the output signal can be obtained from V_{o1} to V_{o2} ($\Delta V_o = V_{o2} - V_{o1}$). The small operating optical wavelength, (2) implies that a small change in the fiber loop length is required in order to obtain the desirable output intensity. For example, if the operating wavelength is 633 nm and the core index is 1.475, the variation of fiber loop length to produce 2π optical phase shift can be found as $\Delta L = \Delta\phi / \beta = (\Delta\phi \cdot \lambda)/2\pi n \approx 430$ nm. Furthermore, if the variation of the fiber loop length is physically controlled to maintain the optical phase (ϕ), the desirable output intensity at any operating point in the vicinity of resonance is stabilized. This can be performed when the fiber loop length is slightly and quickly stretched or shrunk.

III. Stabilization System

1. Principle and Configuration

Figure 3 illustrates the configuration system to compensate the optical phase shift in the ring resonator. The cylindrical piezoelectric device (PZT) is employed as a fiber stretcher. The PZT is wrapped by the fiber in the loop for the purpose of
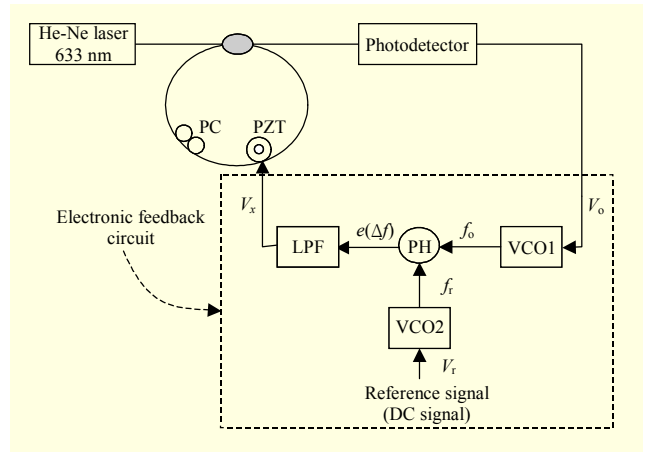
accumulation of loop length variation. Hence, the output intensity of the ring resonator (I_3 or V_o) can be intentionally stabilized by adjusting the loop length corresponding to the appropriate voltage applied to the PZT. The electronic feedback circuit, which is the key component, consists of two voltage control oscillator (VCOs), a low-pass filter (LPF), and a phase comparator (PH). The phase comparator is a device used to obtain the phase difference between any two signals. As seen in the figure, the electrical output signal of the fiber ring resonator V_o is sent to VCO1, which in turn generates the frequency f_o. Similarly, the reference signal V_r is fed to VCO2 to produce the frequency f_r. It must be noted that V_r can be defined at any desirable operating point in the vicinity of resonance of the output signal V_o as shown in Fig. 2. That is, V_r may be between V_{o1} and V_{o2}. The PH then compares the variation frequency f_o with the constant frequency f_r. Since the phase difference between f_r and f_o caused by the drift effect occurs, an error signal $e(\Delta f)$ is then generated by the PH. After that, the error signal $e(\Delta f)$ is regulated by the LPF. The output of the LPF will produce the DC voltage signal V_x to drive the PZT. When the signal V_x is applied to the PZT, the diameter of the PZT cylinder is slightly changed. This consequently causes a variation in the fiber loop length (ΔL). As a result, the variation in the fiber loop length compensates the change in optical phase, and the drift effect is finally eliminated. By using this technique, the output light intensity is stabilized, even though the fiber ring resonator is perturbed from the environment.

To obtain the appropriate voltage applied to the PZT in the practical system, the relationship between the characteristic of the PZT and the variation of the fiber loop length must be considered. Note that this also relates to the relationship between the output signal of the fiber ring resonator and the optical phase shift in the ring loop. Since the condition used for
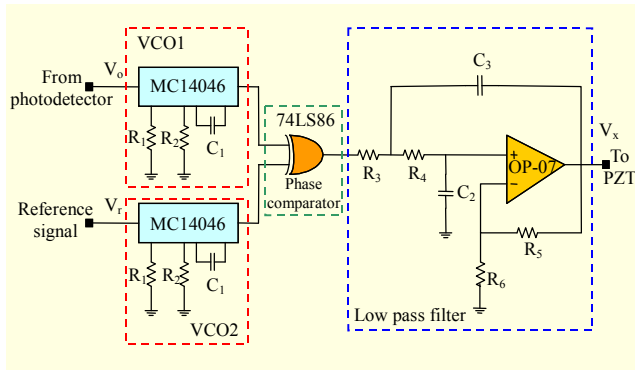
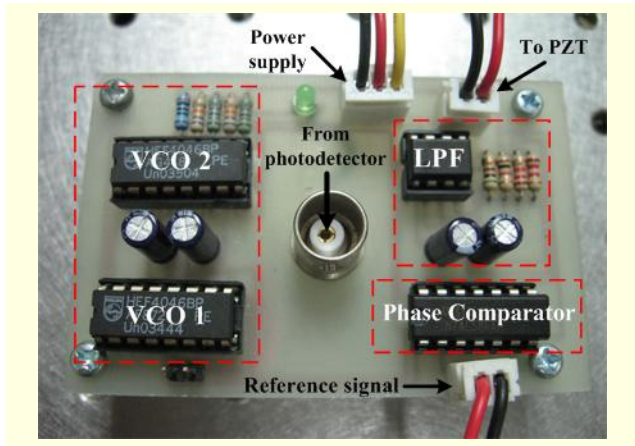Fig. 4. Circuit detail of electronic feedback system.

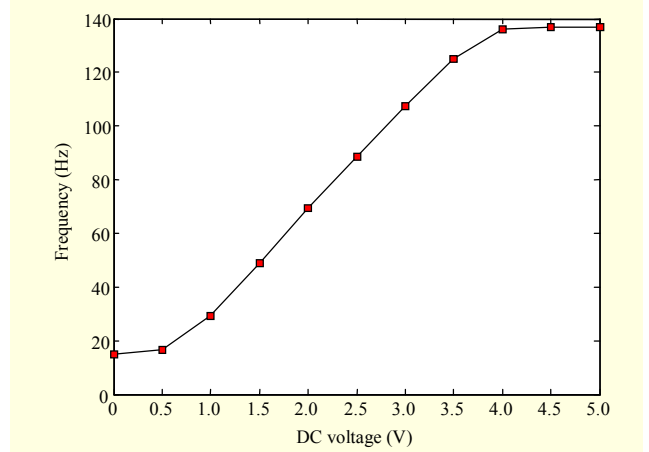Fig. 5. Photograph of electronic feedback circuit.

Fig. 6. Relationship between the DC input voltage and oscillating frequencies of VCO1 and VCO2.
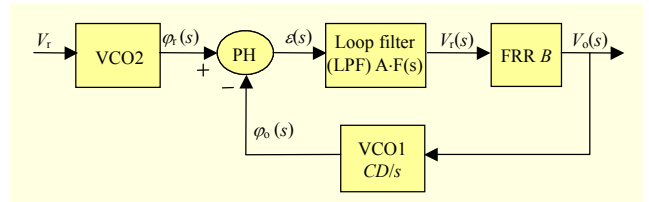
Fig. 7. Block diagram of the electronic feedback loop.

circuit design depends on the electrical components, the parameters of the components must be determined.

In this work, the component details of the electronic feedback circuit and its photograph are shown in Figs. 4 and 5, respectively. The IC#MC14046 is used for both VCOs. The output frequency of the VCOs is determined by the values of R_1, R_2, and C_1. In this case, the oscillating frequency range of the VCOs is from 15 Hz to 140 Hz for the driving input voltage range of 0 V to 5 V. It should be noted that only a particular interval of this operating frequency range can be used in the stabilization system. For example, the capture range in the present case is varied between 20 Hz and 40 Hz, and the lock range is varied between 15 Hz and 50 Hz. In addition, to find the appropriate error voltage resulting from the comparison of the frequencies of the two VCOs, the linear relationship between the DC input voltage and the oscillating frequency of the VCOs as shown in Fig. 6 must be determined. The IC#74LS86 is implemented as a phase comparator by means of an exclusive or gate XOR. The IC#OP-07 made by Sallen and Key Topology is used as the LPF with a cut-off frequency of 140 Hz. The cut-off frequency of the LPF is set by R_3, R_4, C_2, and C_3 [25].

2. System Analysis

Figure 7 shows a block diagram of the electronic feedback circuit employed in the stabilization system in terms of the Laplace transform. The notations in the figure are the following: $\varphi_r(s)$ is the Laplace transform of the input phase function ($\varphi_r(t)$), $\varphi_o(s)$ is the Laplace transform of the output phase function ($\varphi_o(t)$), $\varepsilon(s)$ is the Laplace transform of the phase error ($\varepsilon(t)$), $V_x(s)$ is the Laplace transform of the output loop filter ($V_x(t)$), $V_o(s)$ is the Laplace transform of the output of fiber ring resonator (FRR) ($V_o(t)$), A is the gain of the loop filter, B is the gain of the FRR. Assuming the two VCOs are identical, let C and D be the sensitivity and oscillation gain of the VCOs, respectively. The relationships of the system can be expressed as

$$\varepsilon(s) = \varphi_r(s) - \varphi_o(s), \qquad (3)$$

$$V_x(s) = A \cdot F(s) \cdot \varepsilon(s), \qquad (4)$$

$$V_o(s) = B \cdot V_x(s), \qquad (5)$$

$$\varphi_o(s) = \frac{CD}{s} \cdot V_o(s) + \omega_c(s), \qquad (6)$$

where $\omega_c(s)$ is the Laplace transform of the VCO free-running frequency ($\omega_c(t_0)$). From (3) to (5), $\varphi_o(s)$ can be expanded as

$$\varphi_o(s) = \frac{ABCD \cdot F(s) \cdot \varphi_r(s)}{s} - \frac{ABCD \cdot F(s) \cdot \varphi_o(s)}{s} + \omega_c(s).$$

$$\text{(7)}$$

Let $T = ABCD$, and substituting into (7) a transfer function of the loop filter as $F(s) = 1/(1 + Gs)$, where G is the pole position of loop filter, it can be manipulated as

$$\varphi_o(s) \cdot Gs^2 + \varphi_o(s) \cdot s + T \cdot \varphi_o(s) = T \cdot \varphi_r(s) + \omega_c(s) \cdot s + \omega_c(s) \cdot Gs^2.$$

$$\text{(8)}$$

By applying an inverse Laplace transform to both sides of (8), it becomes

$$G \frac{d^2\varphi_o(t)}{dt^2} + \frac{d\varphi_o(t)}{dt} + T \cdot \varphi_o(t) = T \cdot \varphi_r(t) + \frac{d\omega_c(t_0)}{dt} + G\frac{d^2\omega_c(t_0)}{dt^2}.$$

$$\text{(9)}$$

Since the VCO free-running frequency ($\omega_c(t_0)$) is constant, the first and second derivation of this term is zero. Therefore,

$$G\frac{d^2\varphi_o(t)}{dt^2} + \frac{d\varphi_o(t)}{dt} + T \cdot \varphi_o(t) = T \cdot \varphi_r(t). \qquad \text{(10)}$$

The solution of $\varphi_o(t)$ can be determined by solving this differential equation. In general, $\varphi_o(t)$ is composed of two parts, namely, a homogeneous solution (natural response) and a particular solution (force response). In this case, only the steady state response is of interest. The natural response is therefore ignored [26]. To determine the force response, let $\varphi_r(t)$ be

$$\varphi_r(t) = \omega_r t + \theta_r, \qquad \text{(11)}$$

where ω_r is the input angular frequency, and θ_r is the input phase constant. Then, $\varphi_o(t)$ has the form of

$$\varphi_o(t) = at + b, \qquad \text{(12)}$$

where a and b are unknowns. By replacing $\varphi_o(t)$ shown in (12) into (10), then

$$G\frac{d^2(at+b)}{dt^2} + \frac{d(at+b)}{dt} + T \cdot (at+b) = T \cdot (\omega_r(t) + \theta_r). \text{(13)}$$

Hence,

$$(T \cdot at) + a + (T \cdot b) = (T \cdot \omega_r t) + (T \cdot \theta_r). \qquad \text{(14)}$$

By comparing the coefficients in (14), we get $a = \omega_r$ and $b = \theta_r - \omega_r / T$. Then,

$$\varphi_o(t) = \omega_r t + \theta_r - \frac{\omega_r}{T}. \qquad \text{(15)}$$

From (3), the relationship of the output of the phase comparator in the time domain can be written in terms of phase difference $\varepsilon(t)$ as
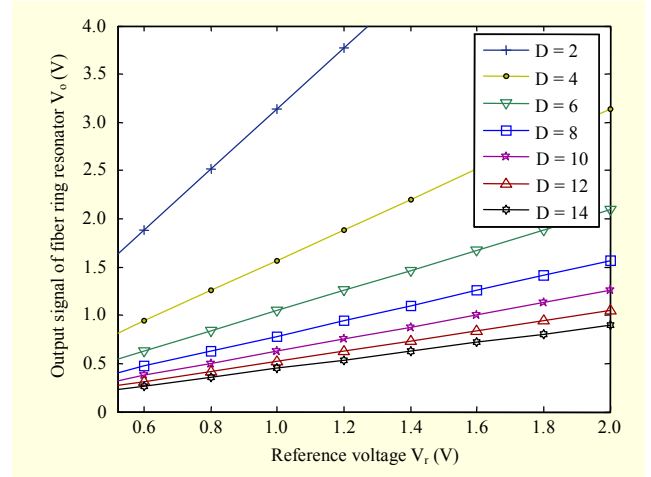
Fig. 8. Oscillation gain of VCO.

$$\varepsilon(t) = \varphi_r(t) - \varphi_o(t) = (\omega_r t + \theta_r) - \left(\omega_r t + \theta_r - \frac{\omega_r}{T}\right) = \frac{\omega_r}{T} = \frac{2\pi f_r}{T}.$$

$$\text{(16)}$$

Regarding the current work, the sensitivity of VCO (C) can be found from the properties of VCO2 shown in Fig. 6 as 38.4 Hz/V. Then, the output frequency of VCO2 (f_r) is obtained as $f_r = C \cdot V_r = 38.4 \cdot V_r$. Assuming that the LPF is an ideal filter, that is, $F(s) = 1$, the expression of the output signal of the fiber ring resonator given in (5) in the time domain can be found as $V_o(t) = AB \cdot \varepsilon(t)$. By using the expression of $\varepsilon(t)$ in (16) and substituting $f_r = C \cdot V_r$, the relationship between the output signal of the fiber ring resonator (V_o) and the reference voltage (V_r) can be finally obtained as $V_o(t) = 2\pi \cdot V_r / D$. Figure 8 plots the output signal V_o as a function of reference voltage V_r at various oscillation gain values (D) of the VCO. This relationship is quite important because the appropriate oscillation gain must coincide with the response time of the output signal of the fiber ring resonator. Hence, the slope of V_o in Fig. 8 must be the same as the transfer function of the ring resonator at the vicinity of resonance.

IV. System Verification

1. Experimental Results

The fiber ring resonator used in the experiment employs a single-mode fiber (SMF 9/125 FITEL) and a 50:50 single-mode directional coupler. As shown in Fig. 9, part of the fiber loop length was wound around a cylindrical PZT (100 turns), with 5 cm diameter, 5 mm thickness and a piezoelectric coefficient of about 365×10^{-12} C/N which can radially expand to control the optical phase of the ring loop. The loop length of the fiber ring is 18.65 m. The photodetector is a silicon PIN
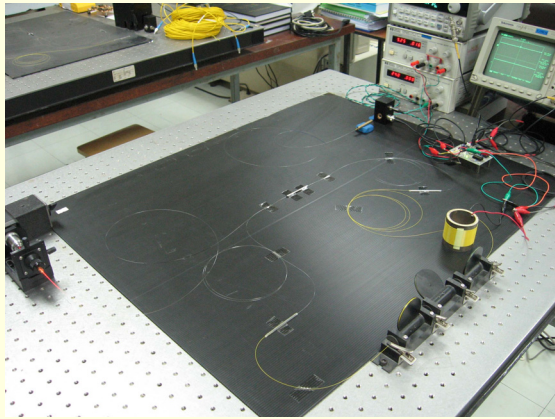
Fig. 9. Experimental configuration for stabilization of fiber ring resonator.

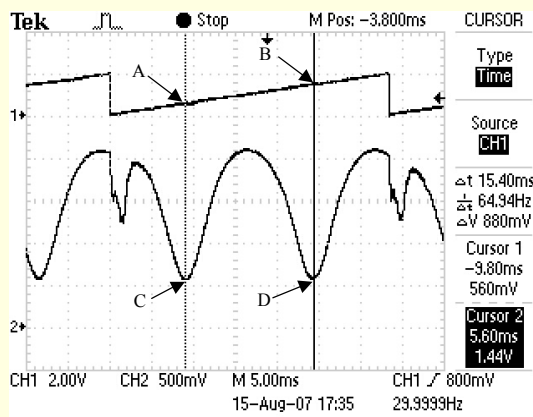Fig. 11. Experimental and analytical results.

Fig. 10. Sawtooth signal applied to PZT (ch. 1) and measured output signal of fiber ring resonator (ch. 2).

detector (Newport model 818-BB-40). A polarization controller (PC), consisting of two rotatable fiber loops, each acting as a quarter wave plate, was used to counter birefringence present in the resonator ring [27]. Thus, the polarization entering the coupler and the fiber ring is the same. A high-power stability He-Ne laser (JDSU Self-Contained He-Ne Laser Model 1507) with a wavelength of 633 nm was used to excite the resonator. To determine the range of the voltage applied to the PZT, only a PZT without a feedback circuit, as shown in Fig. 3, was initially employed. Then, an electrical sawtooth signal with a frequency of 30 Hz and an amplitude of 2 V was applied to the PZT.

Figure 10 shows the electrical output signal V_o of the fiber ring resonator (ch. 2) when the sawtooth signal V_x was applied to the PZT (ch. 1). The applied voltages V_x of 0.56 V at point A and 1.44 V at point B gave a minimum output signal (V_o) of about 0.57 V at points C and D. This result indicates that an applied PZT voltage in the range from 0.56 V to 1.44 V can
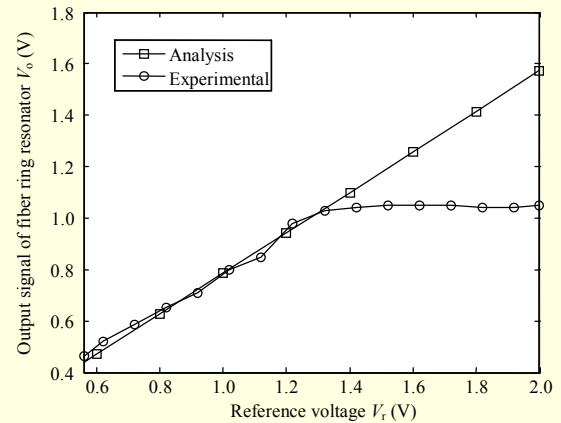
increase the optical phase shift in the fiber ring resonator up to 2π. The maximum output signal (V_o) of 2.1 V seen in the figure also implies that the desirable output signal of the fiber ring resonator can be finely selected by the variation of the applied voltage V_x to the PZT. Note that this applied voltage depends on the present experimental condition. When the stabilization system was completely implemented, starting at the operating point of the ring resonator with respect to the reference voltage at $V_r = 0.57$ V and then increasing its value, the output signal of the resonator was observed as shown in Fig. 11.

As seen in Fig. 11, the slope of the experiment curve (indicated by circles) in the first half is equal to the slope of the transfer function of the fiber ring resonator (indicated by squares) in the same region. Then, the experimental result shows good agreement with the characteristic of the fiber ring resonator when choosing the oscillation gain of the VCO at $D = 8.0$ (obtained from Fig. 8). As the reference voltage is increased, the output signal increases according to the transfer function characteristic of the fiber ring resonator. When the reference voltage is about 1.4 V and beyond, the output signal of the fiber ring resonator remains constant at a value of about 1 V because the electronic feedback circuit is operating out of the lock range. It should be recalled from Fig. 6 that the 1.4 V reference signal relates to the VCO frequency of 50 Hz, which is the maximum frequency of the lock range of the VCOs, and voltages over 1.4 V are out of the lock range. Note that the output voltage of 1 V does not reach the maximum intensity of the ring resonator in the present system.

Figure 12 shows the output signal of the fiber ring resonator when the stabilization system is off and when it is on. Without the stabilization system, as shown in Fig. 12(a), the output signal is unstable due to the drift effect. Once the stabilization system is operated and the reference voltage is fixed, the output signal remains constant. That is, the environment sensitivity is then eliminated. This verifies the validity of the proposed
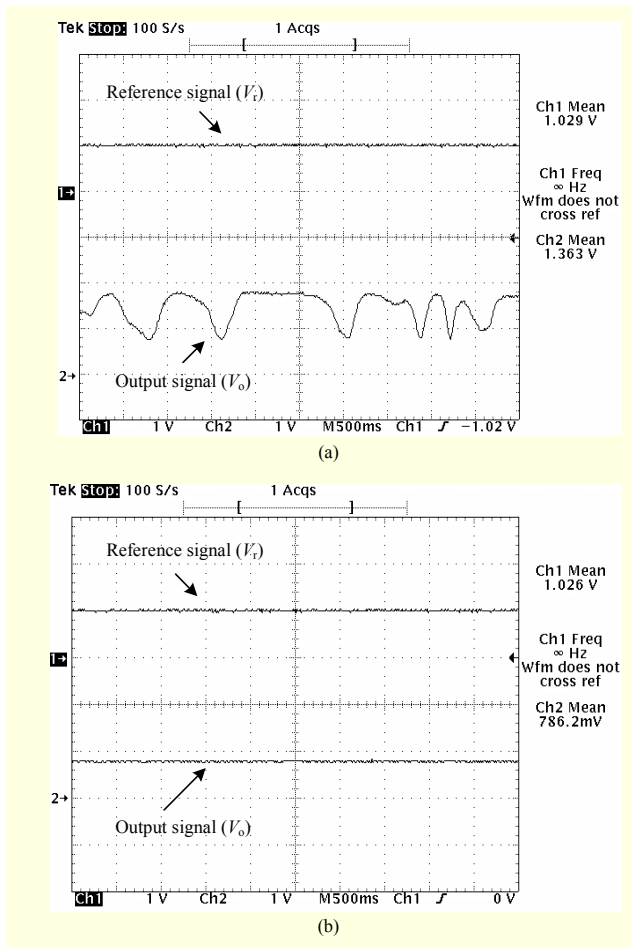
Fig. 12. Measurement of the reference signal and the output signal of fiber ring resonator when electronic feedback circuit is (a) off and (b) on.

Fig. 13. Equivalent models of various stabilization systems.
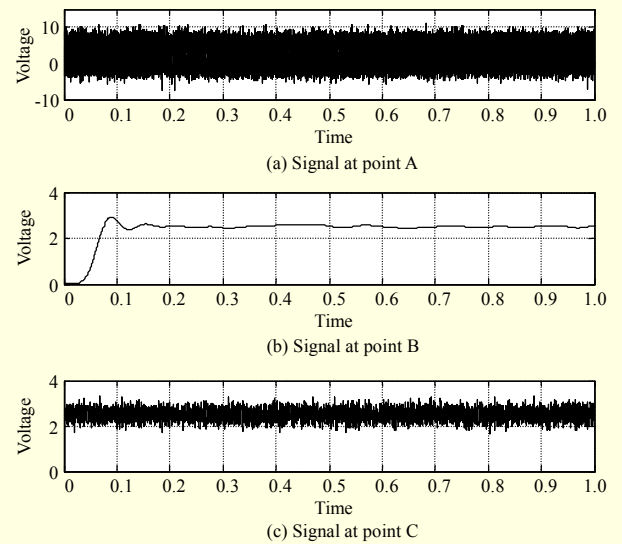
Fig. 14. Simulation results of stabilization systems shown in Fig. 13.

optical stabilization system.

2. Comparison to the Previous Works

To compare the performance of the proposed stabilization system with models previously demonstrated in [15] and [16], equivalent models using the MATLAB Simulink program were set up as shown in Fig. 13. The driving signal to the PZT from different models is selected by the switch S_w. Here, A refers to condition in which the fiber ring resonator is operating alone; B refers to the proposed stabilization system; and C refers to the stabilization system proposed in previous works, consisting of a differential amplifier (Diff Amp.) and an LPF [15], [16]. The output signal of the fiber ring resonator (DC signal) with additional noise (drift effect) is put into the model. In model B, the reference signal is combined in a differential amplifier to produce an error signal. The error signal is sent through the LPF. Consequently, the output signal from the LPF produces the DC voltage to drive the PZT.
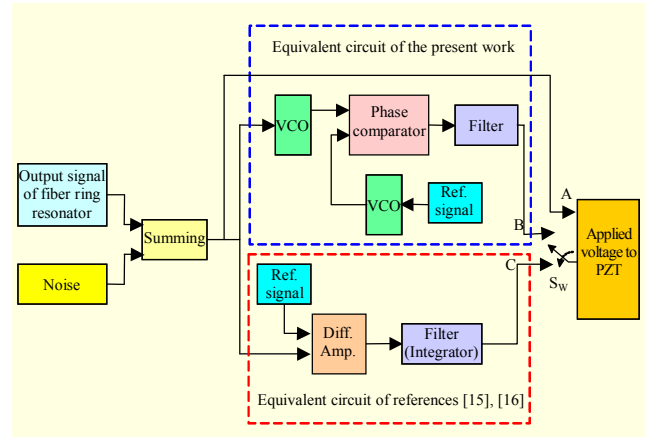
The simulation results for each model are shown in Fig. 14. Figure 14(a) shows the noisy driving signal to the PZT when the fiber ring resonator is operating alone. Figures 14(b) and (c) show the driving signals to the PZT of the proposed and previous stabilization systems, respectively. In the proposed model, the driving signal to the PZT at 2.5 V in relation to the desirable reference signal is investigated. As expected, the driving signal to the PZT shown in Fig. 14(a) is always unstable due to the drift effect. Comparing Figs. 14(b) and (c), it is evident that the driving signal to the PZT of the proposed system is more stable than that of the previous works. This confirms the system performance as well as the improvement of signal stabilization of the fiber ring resonator. Nevertheless, the LPF of the proposed system must be designed to have short transient response in order to quickly reach the steady state for output signal stabilization.

V. Conclusion

A simple electronic feedback circuit system applied to the fiber ring resonator was experimentally and analytically demonstrated for the purpose of stabilizing the optical output intensity of the resonator. The system analysis showed the possibility of eliminating the drift effect which causes the optical phase shift in the ring loop. The output signal of the fiber ring resonator can be constantly controlled at any desirable intensity according to the appropriate reference signal. The proposed system is simple, inexpensive, and effective. The operation of the proposed stabilization system is limited by the lock range of the VCO frequency and the response time of the transient state of the LPF.

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