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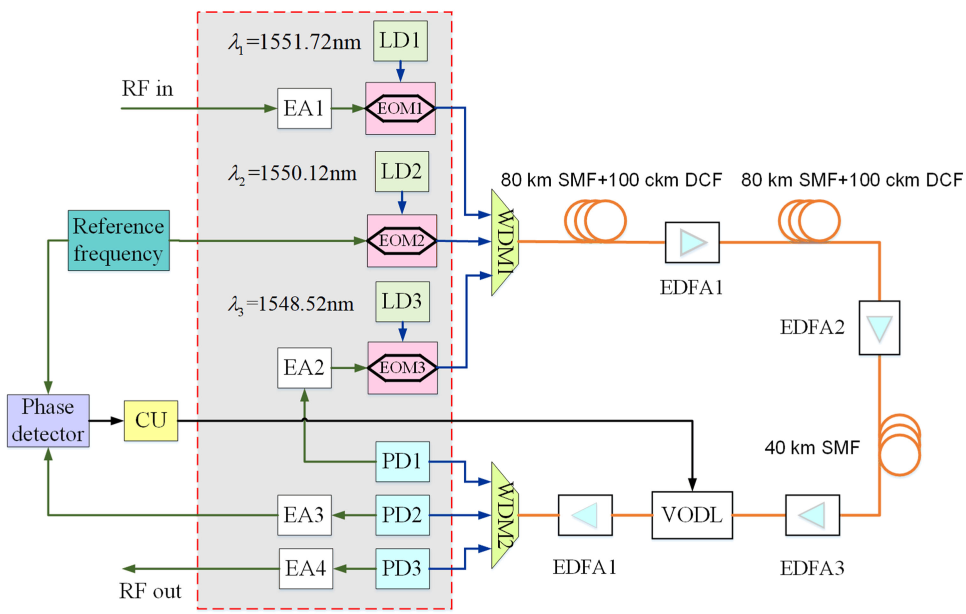

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Active Delay Stabilization of a 440-km Fiber Link in a Wideband Microwave Delay System

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Abstract: In this paper, a wideband microwave delay system with an equivalent 440-km fiber link is presented. The fiber link propagation delay fluctuation, suffering from temperature variation, is detected incorporating with a reference RF signal. With the help of a variable optical delay line, the wideband microwave frequency output is phase-stabilized. A system figure of merit is investigated in detail. The results show that, with dispersion compensation, the fiber-optic delay system can operate for the frequencies up to 38 GHz. Moreover, the fiber-optic system can provide a noise figure of below 40 dB, a signal-to-noise ratio of above 51 dB and a spur level of less than –56 dB for the delayed wideband microwave frequency signal. An additive phase noise of –116 dBc/Hz at the 10 kHz offset frequency can be guaranteed for a 1 GHz frequency. With active delay stabilization, the 38 GHz frequency delayed achieves an Allan deviation of 5.8×10^{-13} /s and 5.4×10^{-16} /10^3s, respectively.

Index Terms: Fiber optics system, instrumentation and metrology.

1. Introduction

Over the past decades, fiber-optics has been intensively investigated and pushes the frontiers of microwave technology. With its unique advantages of broad bandwidth, low loss and high immunity to electromagnetic interference etc., optical fiber links can provide the required delays for a wide variety of high-precision signal processing applications [1]–[5]. However, the delay time varies with the ambient temperature and vibration [6], [7] etc. As a result, the received frequency at the remote site is not stable. And it will be a serious and unacceptable problem when the employed optical fibers are long enough.

To attain a stable frequency at the receiving end, voltage-controlled oscillator, phase shifter and phase conjugation etc. can be employed to pre-compensate the frequency at the transmitting end [8]–[11]. Nevertheless, the phase or frequency variation of transmitted frequency is frequency-dependent. The schemes above, resolving from the frequency domain, are not suitable for wide-band frequency transmission. For wideband microwave frequencies, the optical fiber propagation delay can be stabilized by true time delay controller, such as fiber stretcher, temperature-controlled fiber spool and wavelength-tunable optical source etc. [12]–[16]. However, the correcting signal for the true time delay controller, which is related to the fiber link propagation delay variation, cannot be directly derived from the transmitted wideband microwave frequencies. A reference radio

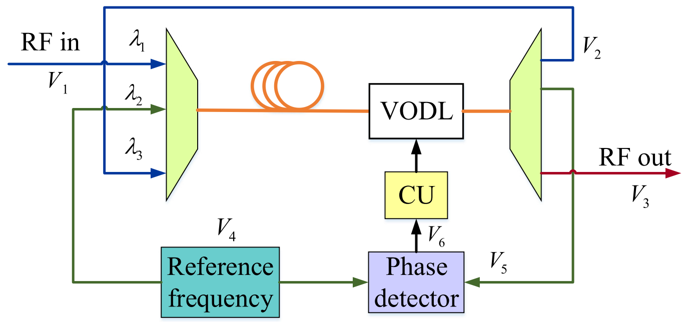


Fig. 1. Schematic structure of presented wideband microwave frequency delay system with a phase-stabilized optical fiber link. VODL: variable optical delay line; CU: control unit.

frequency (RF) signal can be introduced as a probe to sense the fiber propagation delay variation. By adjusting the wavelengths of optical sources, delay-stabilized transmissions for wideband microwave frequencies have been successfully demonstrated [13], [14]. Nevertheless, the large existing chromatic dispersion of fiber link will block wideband microwave frequency transmission due to power fading [17]. Moreover, as the fiber link extends, the solutions above cannot provide sufficient stabilization for the transmitted wideband microwave frequencies due to the precision-limited wavelength-adjustments.

Previously we proposed the methods for wideband microwave frequency distribution via optical fiber [15], [16]. The fiber link propagation delay fluctuation is detected incorporating with a reference RF signal. With the help of a variable optical delay line (VODL), the output phases of transmitted wideband microwave frequencies are stabilized and aligned at different ends. By this means, the power penalty for the received wideband microwave frequencies can be eliminated in the case of an appropriate dispersion compensation. In this paper, we extend the method to a fiber-optic delay system. A wideband microwave delay system with an equivalent 440 km fiber link is presented. A system figure of merit is investigated in detail. The results show that the fiber-optic delay system can operate for the frequencies up to 38 GHz at least. Moreover, the fiber-optic delay system can provide a noise figure (NF) of below 40 dB, a signal-to-noise ratio (SNR) of above 51 dB and a spur level of less than −56 dB for the wideband microwave frequency signal to be delayed. An additive phase noise of −116 dBc/Hz at the 10 kHz offset frequency can be guaranteed for a 1 GHz frequency. Thanks to the active delay stabilization, the 38 GHz frequency acquires an Allan deviation (ADEV) of 5.8×10^{-13} /s and 5.4×10^{-16} /10^3s, respectively.

This paper is organized as follows: Section 2 presents the principle of presented fiber-optic delay system. Section 3 gives the system structure and evaluates the performances in detail. Section 4 draws the conclusion.

2. Operation Principle

Fig. 1 schematically illustrates the principle of proposed wideband microwave delay system with a phase-stabilized optical fiber link. The wideband microwave frequency signal to be delayed at the transmitting end can be expressed as

$$V_1 \propto \cos(\omega_s t + \varphi_s) \tag{1}$$

where ω_s and φ_s represent the angular frequency and initial phase, respectively.

Following electro-optic (E/O) conversion, the wideband microwave frequency signal (carried by an optical source of λ_1) is coupled into an optical fiber link via a wavelength division multiplexer (WDM). For simplicity, the fiber link delay can be treated as t_f and the one of VODL as t_d. At the receiving end, the wideband microwave frequency signal is picked out by another WDM and recovered back through optic-electro (O/E) conversion. Then the output wideband microwave frequency signal can be denoted as

$$V_2 \propto \cos[\omega_s(t - t_f - t_d) + \varphi_s] \tag{2}$$

To increase the total delay time and reduce the devices employed in practice, we retransmit the wideband microwave frequencies over another optical source of λ_3. Afterwards, the output wideband microwave frequency signal can be dictated as

$$V_3 \propto \cos[\omega_s(t - 2t_f - 2t_d) + \varphi_s] \tag{3}$$

Comparing V_3 with V_1, the additive phase of output wideband microwave frequency is proportional to $2\omega_s(t_f + t_d)$. In general, the fiber link propagation delay, t_f, fluctuates with the ambient environment.

To achieve a stable frequency transmission, a reference RF signal is introduced as a probe to monitor the transmission link propagation delay variation. The reference signal can be expressed as follows.

$$V_4 \propto \cos(\omega_0 t + \varphi_0) \tag{4}$$

where ω_0 and φ_0 represent the angular frequency and initial phase, respectively. Likewise, the reference signal is transmitted along the same fiber link with a third optical source of λ_2. At the receiving end, the reference signal can be given as

$$V_5 \propto \cos[\omega_0(t - t_f - t_d) + \varphi_0] \tag{5}$$

An error signal of V_6, which is related to the fiber link propagation delay, can be obtained from V_4 and V_5.

$$V_6 \propto [\omega_0(t_f + t_d)] \tag{6}$$

The error signal is used to drive the VODL so that the value of V_6 fixes to a constant. In this case, the fiber link delay is stabilized. Therefore, both the reference RF signal and the wideband microwave frequency signal are stable at the receiving end. It should be pointed out that, there exists some residual fluctuation terms resulting from the employed electrical and optical devices along separated paths. However, the residual fluctuation terms can be regarded as constant as usual.

3. Experiment and Results

The structure of presented fiber-optic delay system is shown in Fig. 2. The wideband microwave frequency signal is first amplified by an electrical amplifier (EA), and then carried on an optical carrier by an optical source with a wavelength of 1551.72 nm and a 40 GHz electro-optic modulator (EOM) biased at the quadrature point. After a fiber-optic transmission, the wideband microwave frequency signal is recovered by a 40 GHz photodetector (PD, XPDV2120RA-VF-FP, Finisar). To increase the total delay time and reduce the adopted optical devices, the wideband microwave frequency signal is re-transmitted over another wavelength of 1548.52 nm. The reference RF signal, with a frequency of 1 GHz, is generated by an oscillator and split into two branches. One branch is modulated over a wavelength of 1550.12 nm by an EOM with a bandwidth of 10 GHz, and launched into the fiber link as a probe signal. Following detected by a PD with a bandwidth of 12 GHz, the probe signal is compared with the one of the other branch in a phase detector. An error signal, tracking the fiber link propagation delay variation, is attained and applied to the VODL to stabilize the total system delay time via a control unit (CU). Four EAs in total are used to establish usable RF levels at the system inputs and outputs. A pair of WDMs with a channel spacing of 1.6 nm are employed to separate and combine the three optical signals. And the two WDMs are connected by a 200 km G.652D fiber, the corresponding dispersion compensated fiber (DCF, ~20 km) and four commercially-available erbium-doped fiber amplifiers (EDFAs). The residual dispersion coefficient of fiber transmission link is not beyond 3 ps/nm. It is worth noting that the carrier with reference RF signal lies in the center of the three carriers so that the high order effects of thermal drift and chromatic dispersion from optical

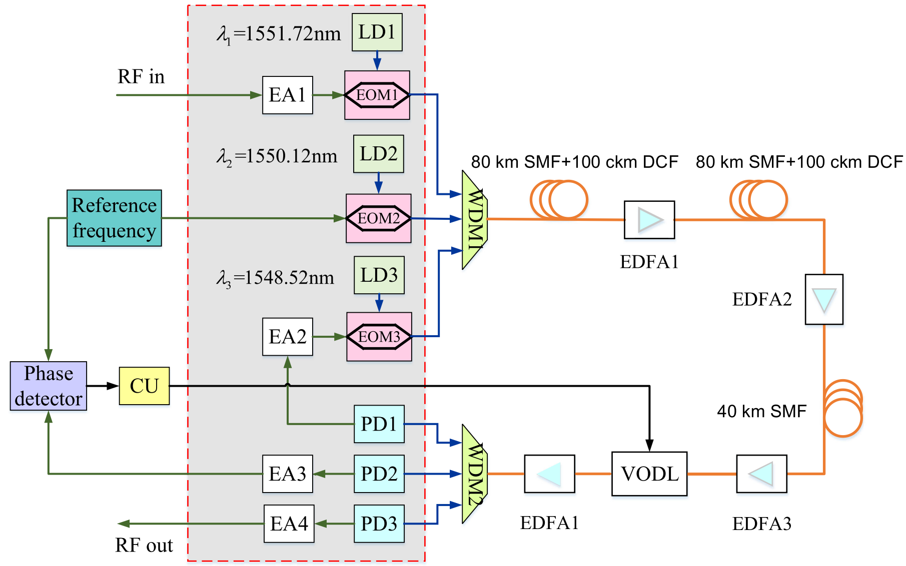


Fig. 2. Configuration of presented fiber-optic delay system. EA: electrical amplifier; LD: laser diode; EOM: electro-optic modulator; PD: photodetector; WDM: wavelength division multiplexer: EDFA: erbium-doped fiber amplifier; DCF: dispersion compensated fiber; VODL: variable optical delay line; CU: control unit.

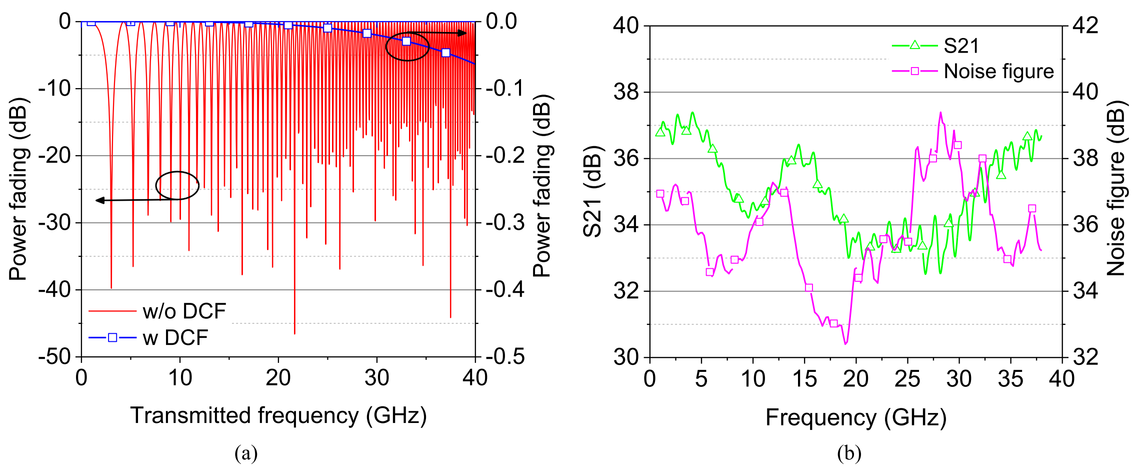
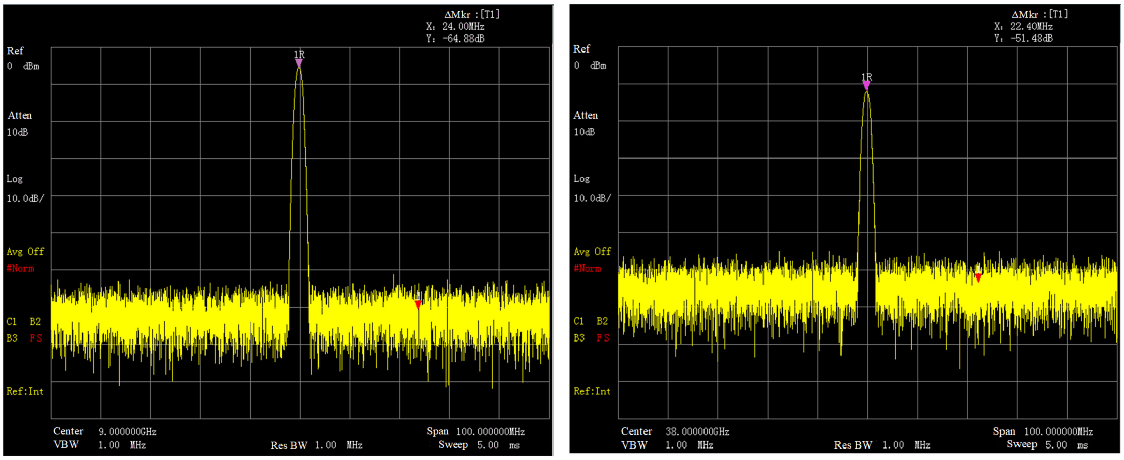


Fig. 3. (a) Theoretical power fading with and without fiber dispersion compensation in a 400 km fiber link. In the case of dispersion compensation, the residual dispersion coefficient is 3 ps/nm. (b) Measured gain parameter and noise figure of the presented fiber-optic delay system.

fiber link can be partly canceled out. The optical gain of each EDFA is carefully set to optimize the SNR of delayed wideband microwave frequency signal.

Fig. 3(a) illustrates the power fading for the wideband microwave frequency signal transmitting over a 400 km G.652D fiber link. When the fiber dispersion is compensated with a residual dispersion coefficient of 3 ps/nm, the result is also shown in theory. One can observe that the power penalty can be neglected in the case of dispersion compensation. Fig. 3(b) gives the measured gain parameter and noise figure of fiber-optic delay system, determined by a vector network analyzer (N5247A, keysight). From the figure, one can see that the electrical gain of fiber-optic delay system varies from 32 to 38 dB for 1–38 GHz frequencies. The results indicate that the presented fiber-optic system enables wideband microwave frequency to be delayed beyond 38 GHz. A better amplitude flatness can be expected when the gain trends of EAs and electro/optic conversions are matched



(a) (b)

Fig. 4. Measured signal-to-noise ratio (SNR) curve taken by a spectrum analyzer over a 100 MHz frequency range. The resolution bandwidth is set to 1 MHz. The input frequency to the fiber-optic delay system is (a) 9 GHz, (b) 38 GHz, respectively.

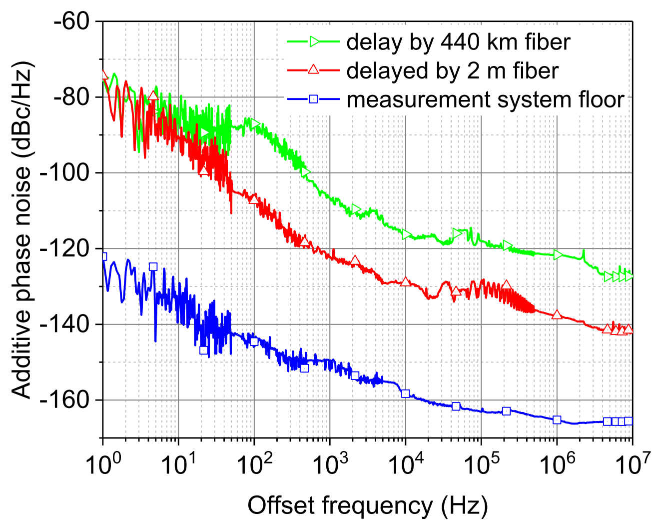


Fig. 5. Additive phase noise spectra of the presented fiber-optic delay system. The measured microwave frequency signal is 1 GHz.

completely. Moreover, as the input frequency changes from 1 GHz to 38 GHz, the NF fluctuates in the range of 32–40 dB, which is adequate for most application cases.

Fig. 4 illustrates the SNR curve taken by a spectrum analyzer over a 100 MHz frequency range. For a 9 GHz CW signal source as input to the fiber-optic delay system, a SNR of 64.9 dB is achieved with a resolution bandwidth of 1 MHz (see Fig. 4(a)). Moreover, a SNR of 51.5 dB is achievable in the case of a 38 GHz input (see Fig. 4(b)). The near-frequency spur level can be acquired by reducing the resolution bandwidth. However, no obvious spur is observed, which means that the spur level is less than −56 dB.

Fig. 5 shows the additive phase noise spectra measured by a signal source analyzer (APPH20G, Anapico). Limited by the phase shifter used for measurement, the results are demonstrated with a 1 GHz frequency signal. Fig. 5 gives the noise floor of the measurement system without connecting the presented microwave delay system. The result of replacing the 220 km fiber with a 1 m fiber in the microwave delay system is also given, which is determined by electrical amplification, optical

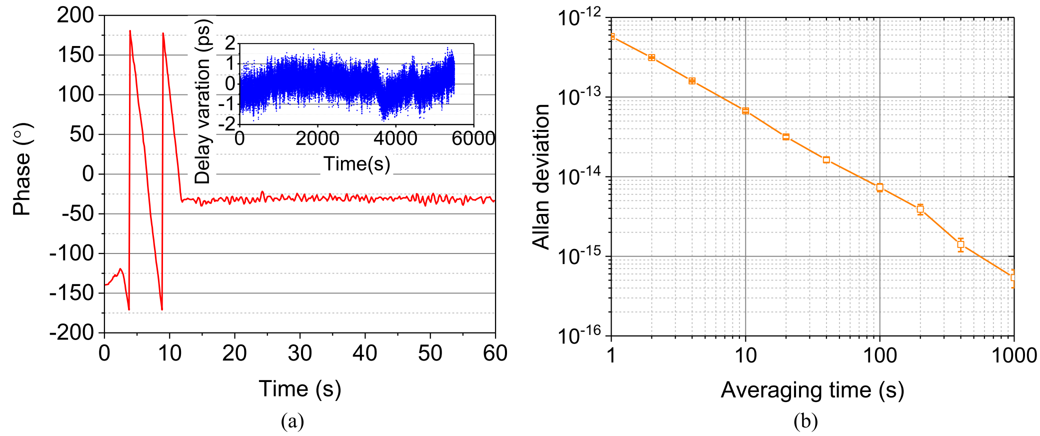


Fig. 6. (a) Phase and delay variation during 5500 s; (b) ADEV of the present fiber-optic delay system. The delayed microwave signal is 38 GHz.

modulation and detection. From the figure, one can see that the additive phase noise is significantly deteriorated for the offset frequencies exceeding 100 Hz as the fiber link extends to 220 km, which mainly comes from multiple optical attenuations and amplifications. However, an additive phase noise of -116 dBc/Hz is still achieved at the 10 kHz offset frequency. As the offset frequency drops down below 10 Hz, the additive phase noise will be affected by the delay stabilization [18]. Fig. 5 shows that the additive phase noises for the offset frequencies less than 10 Hz have almost the same value, regardless of fiber length, which suggests that the delay stabilization works properly.

The delay variation of present fiber-optic delay system is measured directly by N5247A. The whole system is placed in a normal laboratory with an hourly temperature fluctuation of about 3 °C. The output phase of delayed 38 GHz microwave signal with and without delay stabilization is depicted in Fig. 6(a). Thanks to the active delay stabilization, the presented fiber-optic delay system has a delay variation of 4 ps during the 5500 s measurement time (see the inset in Fig. 6(a)), which is consist with the result in Fig. 5. Fig. 6(b) illustrates the corresponding frequency stability. The Allan deviations (ADEVs) amount to 5.8×10^{-13} /s and 5.4×10^{-16} /10^3s, respectively.

4. Conclusion

In conclusion, we present a wideband microwave delay system with an equivalent 440 km fiber link. The output frequencies, up to over 38 GHz, are phase-stabilized. Moreover, the fiber-optic delay system can provide a noise figure (NF) of below 40 dB, a signal-to-noise ratio (SNR) of above 51 dB and a spur level of less than -56 dB for the wideband microwave frequency signal to be delayed. An additive phase noise of -116 dBc/Hz at a 10 kHz offset frequency can be guaranteed for a 1 GHz frequency. An Allan deviation (ADEV) of 5.8×10^{-13} /s and 5.4×10^{-16} /10^3s, respectively, is achieved. The wideband microwave delay system provided opens up many possibilities in high-precision signal processing applications.

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