Photonic generation of tunable phase microwave signal using a feedback controlled birefringent polarization rotator

Kenichiro Tsuji1) and Tomoyuki Uehara1

Abstract The photonic generation of microwaves or millimeter waves using the beat note of two lightwaves is an attractive technique for fiber-wireless communication systems because it enables high-frequency selectivity over the entire radio-frequency region as well as high-speed phase control via electro-optic phase modulators. In this paper, we propose a novel phase control method with small phase drift that uses the polarization dependence of electro-optic phase modulators combined with a feedback-controlled birefringent polarization rotator. The high stability and ultrafast phase shift keying operation of an optically generated microwave signal are experimentally demonstrated.

key words: photonic microwave generation, optical beat note, fiber-wireless communications, birefringent optical fiber
Classification: Optical hardware

1. Introduction

A fiber-wireless communication system that relays microwave or millimeter-wave signals over a low-loss optical fiber is a key technology in next-generation wireless communication networks, for which the effective transmission of wideband signals over several tenths of GHz with reasonable cost is required[1, 2]. Photonic microwave or millimeter wave generation using the optical beat note of two lightwaves is suitable for such fiber-wireless communication systems because it enables phase-controllable high-speed data encoding with a photonic scheme while a radio-frequency (RF) carrier is generated in a remote antenna[3, 4].

In general, there are two types in photonic generation. One type uses two laser sources whose optical frequency difference is precisely controlled with the RF carrier frequency[5, 6, 7, 8, 9] and the other type uses modulation sidebands from a single laser source[10, 11, 12, 13, 14]. The former type have the advantage of being able to generate an RF carrier of over 100 GHz that can readily be selected by tuning the optical frequency of source lasers. However, the stability of the carrier frequency tends to be low since the optical frequency stability of source lasers is intrinsically low compared to the frequency stability of the electrical signal. Thus, some applications that need precise phase adjustment, such as directional antennas based on array antennas[15, 16, 17], are difficult to realize using a scheme with two laser sources. The latter type has a highly stable carrier frequency because the stability is determined by that of the RF signal generator used for modulation irrespective of the optical frequency stability. Double-sideband suppressed-carrier (DSB-SC) modulation is a good candidate for making such modulation sidebands[18, 19, 20, 21]. However, the two sidebands have to be separated into different optical paths for remote phase control[22, 23]. This can cause a serious phase drift of the generated RF carrier as the optical phase difference is directly related to the optical path length and is very sensitive to environmental temperature. Thus, applying a sideband scheme to an array antenna is difficult.

The orthogonally polarized separation of two sidebands is a possible solution because it allows a different phase shift for each polarization mode based on the polarization dependence of an optical phase modulator without separating the optical path[24]. To separate two sidebands into orthogonal polarization modes, configurations that use a polarization-maintaining fiber Bragg grating (PM-FBG) have been reported[25, 26, 27]. However, the power efficiency of this method is relatively low because half of the power of each sideband is discarded in the PM-FBG. In addition, the operation frequency of the RF carrier is limited by the original birefringence of the PM-FBG, which is difficult to control in fabrication. Chi et al. reported a method that uses the birefringence of a polarization-maintaining fiber (PMF) to separate the sidebands into orthogonal polarization modes[28]. In this configuration, there is no limitation on the operation RF frequency since it can be adjusted via the length of the PMF. However, the birefringeance of the PMF is sensitive to the PMF length or, equivalently, to the temperature[29, 30], which makes stable operation difficult.

In this paper, we propose and demonstrate a novel control scheme of the birefringence of the PMF in Ref. 28. To compensate for the phase drift, we introduce a feedback scheme for the birefringence in the PMF that uses the carrier wave before DSB-SC modulation as the monitor light. The stable operation of the proposed method is demonstrated.

1) Department of Communications Engineering, National Defense Academy, 1–10–20 Hashirimizu, Yokosuka-shi, Kanagawa 239-8686, Japan
a) kentsuji@nda.ac.jp

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2. Frequency-dependent polarization state rotator using birefringent optical fiber

The main device in the proposed method is a frequency-dependent polarization state rotator that uses a birefringent optical fiber. The operation principle is schematically shown in Fig. 1. When a linearly polarized optical wave is injected into the birefringent optical fiber with a 45-degree polarization direction with respect to the principal axis, the fast and slow modes are excited. The optical phase difference $\Delta \theta$ at the output of the birefringent optical fiber of length $L$ is given by

$$\Delta \theta = \frac{2\pi \nu}{c}(n_s - n_f)L = 2\pi \nu \Delta \tau$$  \hspace{1cm} (1)

where $\nu$ is the optical frequency, $n_s$ and $n_f$ are the refractive index of the slow and fast axes of birefringence, respectively, and $c$ is the speed of light in vacuum. In Eq. 1, $\Delta \tau = (n_s - n_f)L/c$ is often called the polarization mode dispersion, which represents the amount of birefringence. When two optical sidebands created by DSB-SC modulation are injected into the birefringent optical fiber, if $\Delta \theta = 2m\pi$ for the upper sideband $(\nu_1)$ and $\Delta \theta = (2m + 1)\pi$ for the lower sideband $(\nu_2)$, where $m$ is an integer, or vice versa, the upper and lower sidebands will be orthogonally polarized at the output. This condition is given by

$$\Delta \tau = \frac{1}{2\Delta \nu}$$  \hspace{1cm} (2)

where $\Delta \nu(= \nu_1 - \nu_2)$ is the frequency separation of the two sidebands. For example, a $\Delta \tau$ of 25 ps is required to generate a 20-GHz RF signal that corresponds to a few tenths of meters if a typical PMF, such as PANDA fiber, is used as the birefringent medium[31]. The polarization rotator can separate two sidebands into orthogonal modes in a single optical path, which enables phase control of the beat signal using the polarization dependence of an electro-optic phase modulator. However, since $\Delta \tau$ is a function of $L$, the relatively long fiber length of the birefringent medium is undesirable for stability. Therefore, we introduce an active control scheme for the birefringence, as described in the next section.

Fig. 1. Illustration of the operation principle of the polarization rotator.

3. Experimental setup

Figure 2 shows the experimental setup. The setup is primarily constructed from PMFs and devices. A single-frequency light wave from a laser diode (LD) is sent to a nested Mach-Zehnder modulator, in which two sideband components with a frequency separation of 17.0 GHz are generated by a modulation signal at 8.5 GHz (DSB-SC modulation). These sideband components (red and blue arrows) are coupled into a birefringent section as a polarization rotator through a polarizer with a 45-degree rotating connection, as explained above. The birefringent section is constructed from lithium niobate (LN)-based phase modulator 1 (PM1) and a 10-m-long PMF (Fujikura PANDA fiber), which enables precise birefringence control. The total $\Delta \tau$ of the birefringent section is about 29.4 ps. The amount of birefringence is electrically controlled via PM1 to make the polarization state of the output sidebands orthogonal. The orthogonal sidebands are coupled to phase modulator 2 (PM2) with a 45-degree rotating connection, in which the phase difference between the two sidebands is controlled for the phase control of the beat signal. The orthogonal sidebands interfere with a polarizer, which is connected with a 45-degree rotation. The RF beat signal is generated in a photodiode (PD) and then amplified by an erbium-doped fiber amplifier (EDFA). It is observed using a broadband oscilloscope (OSC).

To monitor the state of the polarization rotator, the light wave before DSB-SC is tapped and injected from the opposite end of the birefringent section through a polarization beam splitter (PBS) and a 10-dB tap coupler. Since the PBS and the polarizer in front of PM1 constitute the birefringent optical filter for the monitor light (green arrows), the state of the polarization rotator can be detected from the output power of the monitor light. Thus, we can make the state of the polarization rotator constant using the feedback scheme via bias voltage $V_b$ of PM1. In the setup, the output polarization state can also be monitored directly using the optical spectrum analyzer (OSA) connected to the PBS.

4. Experimental results

4.1 Separation of upper and lower sidebands using birefringent optical fiber

Figure 3 shows example measurements of the input and output spectra of the birefringent section in Fig. 2. The black curve shows the input DSB-SC spectrum measured at the monitor port in Fig. 2. An acceptable DSB-SC spectrum with a carrier suppression ratio of more than 22 dB can
be obtained. The red curve shows the output spectrum measured via the PBS for a bias voltage $V_b$ adjusted to maximize the power of the lower sideband. In Fig. 3, only the lower sideband component is observed, which shows that the upper and lower sidebands are made orthogonal by propagating through the birefringent section. Note that the power loss of the lower sideband in Fig. 3 includes the coupling loss of the 10-dB tap coupler used for polarization state monitoring. The practical loss in the birefringent section is about 4.5 dB, which is mostly due to the loss of PM1. Total loss of our setup is about 30 dB including the insertion loss of DSB-SC modulator (9 dB) and its modulation efficiency (12 dB) that can be compensated with a conventional optical amplifier. An improvement of the insertion loss will be possible by using an all-fiber-based birefringent control section, for example, a PMF stretcher driven by a piezoelectric actuator or temperature-controlled PMF by a Peltier device.

Figure 4 shows the measured spectrum powers as a function of bias voltage $V_b$ of PM1. The black circles are carrier powers that propagate in the opposite direction in the birefringent section, as measured with a power meter. The blue triangles and red rhombuses are the upper and lower sideband powers, respectively, measured with an OSA via the PBS. The solid curves are sinusoidal fittings for the measured plots. The periodical variation of these spectra shows that the output polarization state can be controlled by $V_b$. From Fig. 4, the upper and lower sidebands are orthogonal when $V_b$ is around -1.5 V or 2.5 V. Note that the phase differences between the carrier and the two sidebands variation are exactly $\pi/2$ since these components have the same frequency separation via optical modulation. Thus, the output polarization state of the two sidebands can be detected by measuring the carrier power. If we control $V_b$ so that the carrier power becomes half of its peak power by using the feedback scheme, the polarization state of the output sidebands can be maintained in the orthogonal state. Note that the birefringent section works as a wavelength dependent optical filter for backward propagating carrier component, but works as a wavelength dependent polarization rotator for forward propagating sideband components, that is, both sidebands are not filtering out. Thus the proposed scheme does not influence power efficiency essentially in contrast to filter-based schemes.

After first adjusting the two sideband powers to their maximum and minimum points and enabling feedback control, we measured the power evolution over the elapsed time. Figure 5 shows the measured upper (blue plots) and lower sideband (red plots) powers as functions of elapsed time, where feedback control is disabled after 30 minutes. When the feedback control is on (solid circles), both sideband powers are almost constant, indicating that polarization orthogonality is well maintained. A polarization extinction ratio of more than 26 dB was obtained under feedback control. In contrast, the results obtained after feedback control was disabled (crosses) show that the polarization state changes over time.

4.2 Phase control of beat signal
To verify the phase controllability of the proposed method, we measured the phase shift keying (PSK) beat waveforms
after a rectangular phase control signal was applied to PM2. In this measurement, the control signal is generated using a pulse pattern generator (PPG) synchronized with the modulation signal of DSB-SC modulation as shown in Fig. 2. Figure 6 shows examples of the control and beat signal waveforms. The repetitive frequency of the control signal is exactly set to 1/64 of the beat signal frequency (17 GHz) and the corresponding beat waveform is triggered by the positive edge of the control signal. As shown, the proposed method can generate an acceptable PSK beat signal according to the control signal.

![Figure 6](image)

**Figure 6.** (a) Rectangular phase control signal and (b) corresponding measured beat waveform in PSK format.

Figure 7 shows the phase difference between adjacent symbols as a function of the voltage amplitude of the applied control signal. The results confirm a linear response of the beat signal phase to the control signal amplitude. The voltage amplitude of the control signal for a half-wave shift in our experiment was estimated to be about 4.8 V$_{p-p}$.

![Figure 7](image)

**Figure 7.** Measured phase difference between adjacent symbols as a function of applied voltage to PM2.

Finally, we measured the degree of the phase stability of the beat signal in our method. Figure 8 shows the absolute phase drift in the PSK beat signal, where the beat waveform was triggered by the control signal. The solid and open circles show each phase of the two adjacent symbols, respectively. As shown, there is a slow phase drift in the absolute phases, although the relative phase is mostly maintained. In our experiment, however, the absolute phase drift (about 5 rad at maximum) was less than one cycle (2$\pi \approx 6.28$ rad) for 30 minutes without temperature control. This phase drift is relatively small compared to that in a two-optical-path configuration[32]. The remaining phase drifts in Fig. 8 can be attributed to the temperature dependence of birefringence in PM2 and its PMF pigtails (1 m for each in our setup) before the output polarizer. In general, the temperature dependence of birefringence is smaller than that of the original refractive index. Therefore, the proposed method suppresses temperature dependence. The use of a short pigtailed device will further decrease the phase drift. The features of slow and small drift within one cycle could be useful for active phase stabilization since it is not necessary to consider a cycle slip. That will be our next work.

![Figure 8](image)

**Figure 8.** Absolute phase drifts of adjacent symbols in PSK beat signal generation. The solid and open circles correspond to the phase of each symbol when the voltage of control signal in Fig. 6(a) is negative and positive, respectively.

5. Conclusions

This paper proposed a novel control scheme for the birefringence of a PMF for reducing the phase drift in photonic generation. To reduce the phase drift, we adopted a single-optical-path configuration and phase control based on the polarization dependence of an optical phase modulator. In this architecture, the polarization direction of the two modulated sidebands is forced into orthogonal states using a specially designed birefringent medium. We also adopted a novel technique for monitoring and controlling the birefringence for stable operation using a feedback scheme. The experimental results confirmed the birefringence control and its usefulness for stable beat signal generation. Phase controllability with a small phase drift based on a single-optical-
path configuration was also demonstrated.

References


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