LETTER

Photonic phase control of microwave signal by a combination of two intensity-modulated lightwaves using a Mach-Zehnder optical switch

Kenichiro Tsuji^{1, a)} and Tomoyuki Uehara¹

Abstract In next-generation wireless communication, photonic control of a remote array antenna is an attractive technique because it enables both low-loss transmission and high-speed beam forming in the base station. In this paper, we propose a novel remote phase control method with a small phase drift for array antenna driving in a fiber-wireless system. Our idea is based on the combination of two intensity-modulated optical waves at different wavelengths with a constant modulation phase difference, which is produced using wavelength dispersion in the transmission line. The useful features of the proposed method for remote driving of an array antenna are experimentally demonstrated.

Keywords: photonic generation, fiber-wireless communications, array antenna, wavelength dispersion

Classification: Optical hardware (fiber optics, microwave photonics, optical interconnects, photonic signal processing, photonic integration and modules, optical sensing, etc.)

1. Introduction

In next-generation wireless communication networks, the use of millimeter waves will be essential for supporting the huge demand for wireless communications, such as high-definition video transmission or on-demand high-quality applications [1]. Due to the relatively short communication range of millimeter waves in practical applications, a small cell architecture that covers a wide area with many antennas is a straightforward scheme and will be the only solution [2, 3]. Thus, a compact and cost-effective millimeter-wave transmission scheme is essential, and a passive antenna device is suitable. Moreover, a directional antenna based on an array antenna is desired to concentrate and enhance the radiated power in the direction toward a mobile station or to achieve space division multiplex access by fast switching the radiation direction [4, 5].

A fiber-wireless communication system is a prospective candidate for such an architecture because it enables compact and effective transmission of a microwave or millimeter-wave signal between the base station and the remote antenna by virtue of the low loss and small diameter of an optical fiber [6, 7, 8]. Thus, photonic control of the remote array antenna is a key technology [9]. In this architecture, fast and stable operation is a matter of special importance. In

addition, completely passive operation in the remote station is desirable.

Photonic generation using the optical beat note of two lightwaves is a promising technique for fast and passive operation because the phase of the generated electric wave can be controlled with an ultrafast optical phase modulator, while the microwave or millimeter wave is passively generated in a remote station [10, 11, 12]. Using two light sources with different wavelengths is the simplest scheme, but the frequency stability of the beat signal is low, which makes it difficult to apply to an array antenna [13, 14, 15]. An optical modulation scheme using two sidebands as the light sources for the optical beat has high frequency stability and is more preferable for such applications, but phase control is difficult because producing a phase difference in two sidebands is not easy. The straightforward method is that the phase of one sideband is changed after the two sidebands are separated into different optical paths and are then recombined [16, 17]. This method, however, often induces a large phase drift because the different optical paths generally have a different temperature dependence. Another method has been reported in which the polarization dependence of the phase modulator is used to produce the phase difference [18, 19, 20, 21, 22]. This method has an advantage of small phase drift because the temperature dependence of birefringence is smaller than that of the original refractive index [23].

However, these methods, based on the control of the optical path length nL for phase control, where n is the refractive index and L is the physical path length, are intrinsically sensitive to the environmental temperature. Thus, the phase drift of the generated wave is a serious problem in practical applications. This makes it difficult to apply the optical beat scheme to a remote array antenna.

In this paper, we propose another method to photonic control the phase of microwaves or millimeter waves by a combination of two intensity-modulated (IM) lightwaves with different wavelengths using a Mach-Zehnder-type optical switch (MZ-SW). In this method, the phase is controlled by the power ratio of two IM lightwaves based on the concept of the synthesis of trigonometric functions. Stable phase operation of the generated signal in the remote station, which is located 1.3 km from the base station, is demonstrated using the proposed method.

2. Basic concept of the proposed method

Figure 1 shows the basic concept of the proposed method.

¹ Department of Communications Engineering, National Defense Academy, 1–10–20 Hashirimizu, Yokosuka-shi, Kanagawa 239–8686, Japan

^{a)} kentsuji@nda.ac.jp

Fig. 1 Illustration of the phase control scheme using a composition of two optical signals.

Two lightwaves at λ_a and λ_b are combined with a MZ-SW in which their power balance is altered for phase control. Then, the two lightwaves are simultaneously intensity modulated (IM) by a modulation signal with carrier and data components. These optical IM waves pass through a dispersive medium, such as a chirped fiber Bragg grating, where they experience different propagation delays according to their wavelengths. Thus, a constant modulation phase difference of these IM waves can be produced corresponding to the wavelength difference of the source lasers. The optical IM waves with the constant modulation phase difference are launched into an optical fiber of a transmission line. Finally, the two optical power waves are converted into a single electrical signal in the microwave or millimeter-wave band (hereinafter referred to as the RF signal) with a broadband photodiode (PD) [24]. The phase of the RF signal is determined by the power ratio of the two optical IM waves depending on the modulation phase difference. Unlike the optical phase, since the optical power ratio is basically independent of the optical path length, it is expected that the RF phase is less sensitive to the environmental temperature. Although the RF phase can be controlled by wavelength tuning of the source laser, as has been reported [25, 26, 27], our method has the advantage of achieving both fast and continuous phase control of the RF signal by a single MZ-SW.

In Fig. 1, carrier generation and data encoding are done in a single intensity optical modulator assuming an amplitude shift keying (ASK) format. This configuration is simpler and has an advantage that the fiber line can be utilized as the dispersive medium. However, in this configuration, the transmitted data waveform is affected by the dispersion of the fiber line. In another alternative, a data encoder can be separated and placed between the dispersive medium and the fiber line together with a small dispersive fiber line.

In practical applications for an array antenna, two or more RF channels are needed. Multiple phase-controlled RF signal generation can be achieved by means of a wavelength division multiplexing (WDM) technique [28, 29]. The basic configuration is shown in Section 4.

3. Theoretical analysis

When two independent sinusoidal optical IM waves with an angular frequency ω and a phase difference of $\Delta\theta$ are simultaneously injected into the PD, the output RF signal $S(t)$ is expressed as

$$\begin{aligned} S(t) &= P_a[1 + \sin(\omega t)] + P_b[1 + \sin(\omega t + \Delta\theta)] \\ &= P_a + P_b + A\sin(\omega t + \phi) \end{aligned} \quad (1)$$

where P_a and P_b are the average power of the two original optical waves. A and ϕ are the amplitude and phase of the RF signal, respectively, which are given by

$$A = \sqrt{P_a^2 + P_b^2 + 2P_aP_b\cos(\Delta\theta)} \quad (2)$$

$$\phi = \tan^{-1}\left(\frac{P_b\sin(\Delta\theta)}{P_a + P_b\cos(\Delta\theta)}\right) \quad (3)$$

Therefore, the phase of the output RF signal ϕ can be controlled by P_a and P_b . The optical power balance of two lightwaves can easily be controlled with a MZ-SW. The transfer function for a conventional 2×1 MZ-SW is sinusoidal for the bias voltage, and the transmissivity T excluding the insertion loss is expressed as

$$T = \frac{1 \pm \cos(V_b\pi)}{2} \quad (4)$$

where the plus or minus sign corresponds to the transmissivity from a straight or cross input port, respectively, and V_b is the normalized bias voltage, which is the ratio of the voltage to the half-wave voltage V_π based on an in-phase point.

Figure 2 shows the calculated phase and amplitude of the output RF signal from the PD (Fig. 2(b)) with the transfer function for the MZ-SW (Fig. 2(a)) as a function of the normalized bias voltage when the relative phase difference $\Delta\theta$ is $\pi/2$. The red and blue curves in Fig. 2(a) show the normalized optical powers at λ_a and λ_b , and the dashed line shows the sum of these values. The solid curves in Fig. 2(b) show the phase ϕ of the RF signal. The calculated results show that the phase of the RF signal can be controlled from 0 to $\pi/2$ according to the bias voltage. Since the optical IM waves with a phase difference of $\Delta\theta$ can be selected by a relative wavelength allocation for the two input ports of the MZ-SW, a negative phase shift is also available, as shown by the gray curve in Fig. 2(b). Thus, the relative RF phase difference between two channels can be controlled from $-\pi/2$ to $\pi/2$. As can be seen from the solid curves in Fig. 2(b), the sensitivity of the RF phase is not constant and becomes a maximum at $V_b = 0.5$. Conversely, it is expected that the phase stability is the worst at $V_b = 0.5$.

The dashed curve in Fig. 2(b) shows the normalized amplitude A of the output RF signal. Undesirably, the amplitude is also changed in the proposed method. The amplitude decreases by 30% at $V_b = 0.5$ when $\Delta\theta$ is $\pi/2$. It follows from this characteristic that the power radiated toward the front direction decreases in the array antenna application. Although power degradation with the MZ-SW is unavoidable, operation with a constant amplitude can be achieved by using two optical intensity modulators that control each optical power individually instead of a MZ-SW.

From Eq. (3), the maximum phase shift of the RF phase is $\Delta\theta$ when $P_a = 0$ and $P_b = 1$. Thus the controllable range of ϕ is determined by $\Delta\theta$ ($0 < \Delta\theta < \pi$). A large $\Delta\theta$, however, further decreases the amplitude around $V_b = 0.5$ from Eq. (2). Thus, the controllable range of ϕ and the amplitude degradation around $V_b = 0.5$ are in a trade-off relation. Figure 3 shows the normalized amplitude A at $V_b = 0.5$ and the maximum phase shift ϕ_{max} for $\Delta\theta$. While ϕ_{max} is directly proportional to $\Delta\theta$, the amplitude decreases according to a cosine function. Thus, if we allow a decrease

Fig. 2 (a) Output optical powers of the conventional MZ-SW and (b) amplitude and phase of output RF signal via PD as a function of normalized bias voltage.

Fig. 3 Normalized amplitude at $V_b = 0.5$ and maximum phase shift as a function of $\Delta\theta$.

in amplitude of 50%, a controllable phase range of $\pi/3$ is attainable. The relatively small range of the RF phase is a main limitation of this method. To achieve the full range of the RF phase, another optical switch for a phase shift of π would be needed.

4. Experimental setup

Figure 4 shows the experimental setup, which assumes that an array antenna with two elements is driven. Two sets of a pair of lightwaves at λ_{1a} and λ_{2a} and at λ_{1b} and λ_{2b} from four wavelength-tunable lasers based on an external cavity laser (ECL) are coupled, respectively, and are sent to each input port of a 2×1 MZ-SW. Here, subscripts a and b indicate the two lightwaves corresponding to P_a and P_b in Eq. (1), and the subscripts 1 and 2 indicate the channel number. The power balance between P_a and P_b is simultaneously controlled with the MZ-SW by V_b for both channels. Then, the four lightwaves are intensity modulated to generate a high-frequency optical signal. In this experiment, we used double-sideband suppressed carrier (DSB-

Fig. 4 Experimental setup.

SC) modulation without data encoding with the main purpose of verifying the phase stability of the proposed method. The DSB-SC modulation can generate a double-frequency IM signal and is useful for high-frequency signal generation, such as millimeter-wave generation [12, 30, 31, 32]. Although the setup assumes an application of a millimeter-wave band, the generation frequency is 20 GHz driven by a 10-GHz RF signal due to the bandwidth limitation in our measurement system. A 10%-output optical power is tapped, and the optical spectrum is measured with an optical spectrum analyzer (OSA) to monitor the status of the MZ-SW and DSB-SC modulation. The optical IM waves are amplified by an erbium-doped fiber amplifier (EDFA) and then launched into a transmission line of a 1.3-km standard single-mode fiber (SMF), which also acts as a dispersive medium to create the constant phase difference $\Delta\theta$. The transmitted lightwaves are separated into two sets with a demultiplex (DMAX) optical filter, and the PDs receive the signal from each channel (Ch1, Ch2). Each PD generates a composite RF signal $S(t)$, and they are measured using a broadband oscilloscope (OSC) triggered by the modulation signal.

The number of channels can be increased in principle by coupling twice as many sources of channel number with multiplexers because the maximum phase shift is proportional to $\Delta\theta$ as shown in Fig. 3. The wavelength of each pair has to be properly chosen according to the dispersion. For example, by adding two channels with $\Delta\theta = \pm\pi/4$, a four-channel system can be realized. That is to say, two sets of wavelength pairs with a half-wavelength separation are added to the input port of the MZ-SW. Although the proposed method requires twice as many independent tunable sources of the channel number, wavelength tuning is only required in the initial setup, and fixed-wavelength laser sources could also be used if the wavelength allocation is properly designed. However, a design with a large number of channels requires a relatively wide wavelength bandwidth. Therefore, the wavelength dependence of the MZ-SW or optical modulator will limit the number of channels. Considering the increase in complexity accompanying the increase in laser sources, the proposed method may be suited to a small-channel system.

5. Experimental results

Prior to a phase control experiment, we measured the wavelength dispersion of the SMF that simulates a transmission line between the control station and the remote antenna. Figure 5 shows the measured results. The solid circles show the measured plots, and the solid line is its linear fitting. The vertical axes show the relative time delay and corresponding phase shift for the 20-GHz IM wave normalized by the value

at 1545 nm. From Fig. 5, the wavelength dispersion of the SMF is almost proportional to the wavelength in the 1550-nm band, as shown by the solid line in Fig. 5. The measured dispersion was 23.0 ps/nm (right axis), which corresponds to a phase shift of 2.89 rad/nm for the IM wave at 20 GHz (left axis).

Fig. 5 Measured wavelength dispersion of the SMF.

We defined the wavelength allocation of the source lasers based on the measured dispersion in Fig. 5. The optical frequency difference between two IM waves has to be higher than the detector bandwidth (50 GHz in our setup) because a beat component is added to the output RF signal as the noise component. In the experiment, we adopt a wavelength difference of 0.60 nm (75 GHz@1550nm) between λ_a and λ_b , which gives a maximum phase shift of 1.73 rad with the dispersion of SMF from Fig. 5. Additionally, we set $\lambda_a > \lambda_b$ for channel 1 and $\lambda_a < \lambda_b$ for channel 2, so that a positive phase shift for V_b is produced for channel 1, while a negative phase shift is produced for channel 2, as shown in Fig. 2(b). Thus, the controllable range of the phase difference between channel 1 and channel 2 will be 3.46 rad. The practical wavelengths and frequencies in the experiment are summarized in Table I. The channel spacing was set to 2.0 nm in our setup. A small channel spacing is better for avoiding the wavelength dependence of each device but often causes cross talk in demultiplexing. In practical array antenna applications, the wavelength difference between channels also has to be adjusted since it defines the center direction in the variable range of the radiation wave. In consideration of wavelength allocation, although $\Delta\theta$ allows an uncertainty of $2m\pi$, where m is an integer, a smaller $\Delta\theta$, that is a smaller wavelength difference, is preferred because the time delay is accompanied by the $\Delta\theta$ that limits the data rate in encoding.

Table I Wavelength of source lasers in the experiment.

Channel	Label	Wavelength	Frequency
Ch1	λ_{1a}	1548.10 nm	193.65 THz
	λ_{1b}	1548.70 nm	193.58 THz
Ch2	λ_{2a}	1550.10 nm	193.40 THz
	λ_{2b}	1550.70 nm	193.33 THz

Figure 6 shows example measurements of the optical spectrum at the output of the DSB-SC modulator (left side) and output RF signals (right side) when the bias voltage of the MZ-SW V_B is -0.5 , 1.3 , or 3.1 V, which correspond to $V_b = 0$, 0.5 , and 1 , respectively. The RF signal of Ch1 is a

Fig. 6 Example measurements of the optical spectrum at the output of the DSB-SC modulator (left) and output RF signals (right) when V_b is (a) 0, (b) 0.5, and (c) 1. Vertical axes of the waveforms are the same scale.

composition of two optical waves at λ_{1a} and λ_{1b} and Ch2 is the composition of λ_{2a} and λ_{2b} . As can be seen from Fig. 6, the phases of the output RF signals change according to the power balance between λ_a and λ_b in each channel. On the other hand, the amplitude decreases to 65% for Ch1 and to 60% for Ch2 at $V_b = 0.5$. Although a small difference in the amplitude characteristics for V_b between these channels is observed, the amplitude degradation is substantially the same as the theoretical analysis at $\Delta\theta = 1.73$ rad in Fig. 3. The small difference in the amplitude characteristics between channels could be due to the wavelength dependence of the MZ-SW.

Figure 7(a) shows the phase of two output RF signals as a function of the bias voltage of the MZ-SW. The phases are calculated from the measured waveforms using a Fourier analysis. As predicted in Fig. 2, both the Ch1 and Ch2 phases show the same sinusoidal variation according to the bias voltage, but they have opposite coefficients for the bias voltage. Figure 7(b) shows the phase difference between Ch1 and Ch2. The maximum phase shift was 3.5 rad, which is in good agreement with the prediction from the measured dispersion of the SMF.

Finally, we measured the degree of the relative phase stability of the output RF signal in our method. From Fig. 2, the phase sensitivity is proportional to the maximum phase shift ϕ_{max} . Thus, it is expected that the phase stability depends on $\Delta\theta$ because ϕ_{max} is determined by $\Delta\theta$, as shown in Fig. 3. On the other hand, the controllable range ($2\phi_{max}$) is also determined by $\Delta\theta$. Thus, there is probably a trade-off between the stability and the controllable phase range. Considering practical applications, a controllable phase range of more than π will be required. Therefore, we evaluate the stability under the same conditions as in the above experiments ($\Delta\theta = 1.73$ rad, $2\phi_{max} = 3.46$ rad).

The open circles in Fig. 8 show the absolute phase drifts

Fig. 7 (a) Phases of output RF signals at Ch1 and Ch2 and (b) the phase difference as a function of bias voltage of the MZ-SW.

of the output RF signals in Ch1 and Ch2 with elapsed time with a constant bias voltage of 1.3 V ($V_b = 0.5$, the worst condition for stability). In this experiment, the SMF is placed in a periodic air flow from an air-conditioner in order to simulate temperature fluctuation of the transmission line. The period when the SMF is exposed to the air flow is shown by the shaded areas in Fig. 8. As a result, a slow phase drift can be observed in each RF phase of both channels. The solid black circles in Fig. 8 show the relative phase difference between Ch1 and Ch2. In contrast to the absolute phase, the relative phase is mostly maintained under the external disturbance. The standard deviation of the relative phase for 1-hour operation was 0.041 rad. Under the same conditions, the amplitude stability for each channel was 3.2% and 2.6%, respectively, and the relative amplitude stability between channels was 2.9%. This high stability of the relative phase could sustain remote driving of an array antenna.

The obtained phase stability depends on the length of the SMF in principle. However, the maximum phase drift of the absolute RF phase in Fig. 8 is less than 2π (50 ps at 20 GHz), which corresponds to a length variation of less than 0.01 m, assuming $n = 1.5$. Thus, the relative phase drift attributed to the fiber length is estimated to be 44.5×10^{-6} rad from the dispersion of the SMF (Fig. 5) and the channel spacing of 2 nm. This value is much smaller than the experimental result. Therefore, the remaining drift of the relative phase in Fig. 8 is not due to the SMF and is probably attributed to the temperature dependence of the MZ-SW. In general, the temperature drift of the MZ-SW can be suppressed with a feedback control system. In the proposed method, another output port of a 2×2 MZ-SW can be utilized to monitor the state of the MZ-SW. Such a feedback system will further improve the relative phase stability.

Fig. 8 Phases of output RF signals at Ch1 and Ch2, and the relative phase as a function of elapsed time.

6. Conclusion

This paper proposed a photonic phase control scheme using a composition of two intensity-modulated lightwaves to drive a directional antenna in a fiber wireless communication system. To reduce the relative phase drift of the two generated RF signals in the remote station, we adopted a novel phase control scheme by controlling the power ratio of two lightwaves with a constant phase difference accompanied by wavelength dispersion of a transmission line. The experimental results confirmed the continuous phase controllability of the composite RF wave and are in good agreement with the theoretical analysis based on the measured dispersion. Also, the experiment for 1-hour operation shows high stability of the relative phase even when the 1.3-km-long transmission line is exposed to an external disturbance. Fast and continuous phase controllability with a small phase drift could be useful for remote directional antenna driving.

References

- [1] I.A. Hemadeh, *et al.*: "Millimeter-wave communications: physical channel models, design considerations, antenna constructions, and link-budget," *IEEE Commun. Surveys Tut.* **20** (2018) 870 (DOI: [10.1109/COMST.2017.2783541](https://doi.org/10.1109/COMST.2017.2783541)).
- [2] M. Marcus and B. Pattan: "Millimeter wave propagation; spectrum management implications," *IEEE Microw. Mag.* **6** (2005) 54 (DOI: [10.1109/MMW.2005.1491267](https://doi.org/10.1109/MMW.2005.1491267)).
- [3] S. Rangan, *et al.*: "Millimeter-wave cellular wireless networks: potentials and challenges," *Proceedings of the IEEE* **102** (2014) (DOI: [10.1109/JPROC.2014.2299397](https://doi.org/10.1109/JPROC.2014.2299397)).
- [4] S. Kuty and D. Sen: "Beamforming for millimeter wave communications: an inclusive survey," *IEEE Commun. Surveys Tut.* **18** (2016) 949 (DOI: [10.1109/COMST.2015.2504600](https://doi.org/10.1109/COMST.2015.2504600)).
- [5] A.H. Naqvi and S. Lim: "Review of recent phased arrays for millimeter-wave wireless communication," *Sensors* **18** (2018) 3194 (DOI: [10.3390/s18103194](https://doi.org/10.3390/s18103194)).
- [6] G. Grosskopf, *et al.*: "60 GHz-millimetre-wave generation and beamforming in hybrid-fibre-radio systems for broadband-wireless access," 27th Triennial General Assembly of the International Union of Radio Science (2002) D1.
- [7] X. Yi, *et al.*: "Photonic beamforming based on programmable phase shifters with amplitude and phase control," *IEEE Photon. Technol. Lett.* **23** (2011) 1286 (DOI: [10.1109/LPT.2011.2158815](https://doi.org/10.1109/LPT.2011.2158815)).
- [8] T.P. McKenna, *et al.*: "Photonic beamsteering of a millimeter-wave array with 10-Gb/s data transmission," *IEEE Photon. Technol. Lett.* **26** (2014) 1407 (DOI: [10.1109/LPT.2014.2326332](https://doi.org/10.1109/LPT.2014.2326332)).

- [9] N. Shi, *et al.*: “Optically controlled phase array antenna,” *Chinese Opt. Lett.* **17** (2019) 052301 (DOI: 10.3788/COL201917.052301).
- [10] J. Yao, *et al.*: “Photonic generation of ultrawideband signals,” *IEEE J. Lightw. Technol.* **25** (2007) 3219 (DOI: 10.1109/JLT.2007.906820).
- [11] W. Li, *et al.*: “Photonic MMW-UWB signal generation via DPMZM-based frequency up-conversion,” *IEEE Photon. Technol. Lett.* **25** (2013) 1875 (DOI: 10.1109/LPT.2013.2278867).
- [12] K. Tsuji, *et al.*: “Optically generated phase shift keying microwave signal using optical phase modulator with single light source,” *IEICE Electron. Express* **10** (2013) 20130616 (DOI: 10.1587/elex.10.20130616).
- [13] H. Rideout, *et al.*: “Discriminator-aided optical phase-lock loop incorporating a frequency down-conversion module,” *IEEE Photon. Technol. Lett.* **18** (2006) 2344 (DOI: 10.1109/LPT.2006.885212).
- [14] R. Herschel and C.G. Schaffer: “Phase modulated radio-over-fiber system for high order modulation millimeter wave link,” *IEEE J. Lightw. Technol.* **32** (2014) 3602 (DOI: 10.1109/JLT.2014.2315662).
- [15] P. Pérez, *et al.*: “Photonic generation of microwave signals using a single-mode VCSEL subject to dual-beam orthogonal optical injection,” *IEEE Photon. J.* **7** (2015) 5500614 (DOI: 10.1109/JPHOT.2015.2400391).
- [16] W. Chen, *et al.*: “Photonic generation of binary and quaternary phase-coded microwave waveforms with frequency quadrupling,” *IEEE Photon. J.* **8** (2016) 5500808 (DOI: 10.1109/JPHOT.2016.2548473).
- [17] H.-Y. Jiang, *et al.*: “Photonic generation of phase-coded microwave signals with tunable carrier frequency,” *Opt. Lett.* **38** (2013) 1361 (DOI: 10.1364/OL.38.001361).
- [18] H. Chi and J. Yao: “Photonic generation of phase-coded millimeter-wave signal using a polarization modulator,” *IEEE Microw. Compon. Lett.* **18** (2008) 371 (DOI: 10.1109/LMWC.2008.922136).
- [19] L. Gao, *et al.*: “Photonic generation of a phase-coded microwave waveform with ultrawide frequency tunable range,” *IEEE Photon. Technol. Lett.* **25** (2013) 899 (DOI: 10.1109/LPT.2013.2253455).
- [20] Z. Li, *et al.*: “Photonic generation of phase-coded millimeter-wave signal with large frequency tunability using a polarization maintaining fiber Bragg grating,” *IEEE Microw. Compon. Lett.* **21** (2011) 694 (DOI: 10.1109/LMWC.2011.2170673).
- [21] W. Zhang and J. Yao: “Photonic generation of millimeter-wave signals with tunable phase shift,” *IEEE Photon. J.* **4** (2012) 889 (DOI: 10.1109/JPHOT.2012.2199481).
- [22] J. Ye, *et al.*: “Photonic generation of microwave frequency shift keying signal using a polarization maintaining FBG,” *IEEE Photon. J.* **10** (2018) 5501108 (DOI: 10.1109/JPHOT.2017.2772778).
- [23] K. Tsuji and T. Uehara: “Photonic generation of tunable-phase microwave signal using a feedback-controlled birefringent polarization rotator,” *IEICE Electron. Express* **16** (2019) 20190559 (DOI: 10.1587/elex.16.20190559).
- [24] T. Nagatsuma and H. Ito: *Advances in Photodiodes* ed. G. D. Betta (InTech, 2011) 291.
- [25] J.L. Corral, *et al.*: “True time-delay scheme for feeding optically controlled phased-array antennas using chirped-fiber gratings,” *IEEE Photon. Technol. Lett.* **9** (1997) 1529 (DOI: 10.1109/68.634731).
- [26] S. Akiba, *et al.*: “Photonic architecture for beam forming of RF phased array antenna,” *Optical Fiber Communication Conference* (2014) W2A.51 (DOI: 10.1364/OFC.2014.W2A.51).
- [27] M. Tadokoro, *et al.*: “Optically-controlled beam forming technique for 60 GHz-ROF system using dispersion of optical fiber and DFWM,” *OFC/NFOEC* (2007) OWN2 (DOI: 10.1109/OFC.2007.4348909).
- [28] Y. Liu, *et al.*: “Continuous true-time-delay beamforming for phased array antenna using a tunable chirped fiber grating delay line,” *IEEE Photon. Technol. Lett.* **14** (2002) 1172 (DOI: 10.1109/LPT.2002.1022008).
- [29] A. Yu, *et al.*: “A multi-channel multi-bit programmable photonic beamformer based on cascaded DWDM,” *IEEE Photon. J.* **6** (2014) 7902310 (DOI: 10.1109/JPHOT.2014.2344007).
- [30] J. Ma, *et al.*: “A novel scheme to implement duplex 60-GHz radio-over-fiber link with 20-GHz double sideband optical millimeter-wave transmitted along the fiber,” *Opt. Fiber Technol.* **15** (2009) 125 (DOI: 10.1016/j.yofte.2008.06.007).
- [31] F. Zhou, *et al.*: “Photonic generation of frequency quadrupling signal for millimeter-wave communication,” *Opt. Commun.* **304** (2013) 71 (DOI: 10.1016/j.optcom.2013.04.030).
- [32] S. Shen and W. Yin: “Photonic generation of high-purity 60 GHz millimeter-wave signal requiring only 10 GHz radio frequency local oscillator,” *Opt. Rev.* **25** (2018) 684 (DOI: 10.1007/s10043-018-0461-0).