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Millimeter-wave true-time delay measurement in WDM-based optically controlled array antenna

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Abstract Microwave/millimeter-wave, true-time delay characteristics of WDM-based optically controlled array antenna is experimentally verified. True-time delay characteristics with phase deviation of less than 3 deg. are obtained using 4-element WDM-based optically controlled array antenna in the frequency range from 20 to 40 GHz.

1 Introduction

Optically controlled beam forming of microwave/millimeter–wave phased array antenna is superior in wide/multi-bandwidth operation to microwave/millimeter–wave phase shifters and digital beam forming. Especially optical dispersion technique [1]-[4] has inherently true-time delay characteristics suitable for wide/multi-bandwidth operation, although temperature instability of the delay in the optical fiber is one of the technical issues. However, WDM-based optically controlled array antenna consists of WDM optical sources and an optical dispersion fiber does not cause microwave/millimeter–wave phase instability due to temperature because only the difference in chromatic dispersion at each wavelength within the same SMF is used to control the phase of microwave/millimeter–wave signals. In this letter, we measured the millimeter-wave true-time delay in order to clarify the phase accuracy of the WDM-based optically controlled array antenna.

2 Experimental setup

Figure 1(a) shows schematic diagram of the proposed optically controlled array antenna for transmission. Thick line shows optical component and thin line shows microwave/millimeter-wave one. In the transmitting array antenna, chromatic dispersion of a conventional single mode fiber is used to control microwave/millimeter-wave phase to be fed to each antenna element for beam steering. First, optical carrier $\lambda_1 - \lambda_n$ having different wave length is combined by the optical multiplexer and modulated with microwave/millimeter-wave signal. Next, modulated optical carrier is delayed by the effect of chromatic dispersion at each wave length when it passes the same SMF. Next, each optical carrier $\lambda_1 - \lambda_n$ with different delay is detected by photodiode after DEMUX. Since obtained microwave/millimeter–wave phase at each antenna element is different, antenna beam is able to be steered to arbitrary direction by adjusting the optical wavelengths and SMF length. Delay time difference τ_{opt} between adjacent wavelengths can be expressed as

$$\tau_{opt} = DL\Delta\lambda_{opt}, \qquad (1)$$

where D is wavelength dispersion of the SMF, L is the SMF length and $\Delta\lambda_{opt}$ is wavelength spacing. Microwave/millimeter–wave phase difference $\Delta\varphi$ between adjacent antenna element can be expressed as

$$\Delta\varphi = 2\pi DL\Delta\lambda_{opt} f_{RF}, \qquad (2)$$

where f_{RF} is microwave/millimeter–wave frequency.

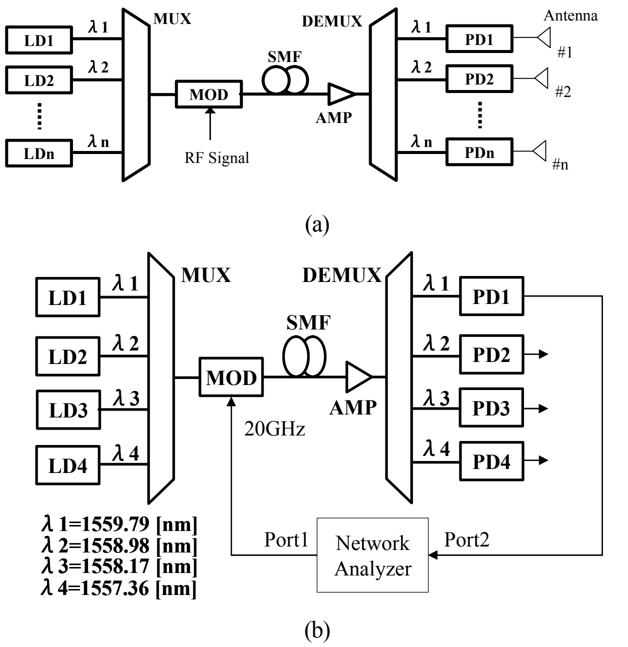

Fig. 1 (a) Schematic diagram and (b) experimental setup of WDM-based optically controlled array antenna.

Since only one SMF acts as microwave/millimeter–wave phase shifters, number of phase shifters can be reduced when optical carrier of a different wavelength is assigned to each antenna element. In addition, since wavelength dispersion characteristics of the SMF is invariant and each wavelength can be adjusted to control the phase of corresponding microwave/millimeter–wave signal, WDM-based control is less affected by surrounding environmental condition including temperature and expected as one of ways to be able to attain very stable microwave/millimeter–wave phase shifters. Figure 1(b) shows experimental setup of WDM-based optically controlled array antenna. We carried out phase control experiments using 4-element array antenna for transmission in the frequency range from 20 to 40 GHz. Four DFB lasers with wavelengths of 1559.79, 1558.98, 1558.17 and 1557.36 nm are multiplexed and modulated by 20 - 40 GHz signals. Length of SMF for optical delay is changed in proportional to micro/millimeter-wavelength to investigate frequency dependence on phase accuracy. Finally, each delayed optical signal is demultiplexed and detected to 20 – 40 GHz. Microwave /millimeter–wave phase of each element was relatively measured using network analyzer by switching the output of each photodiode.

3 Experimental results

Figure 2 shows obtained 20 - 40 GHz phase characteristics of 4-element WDM-based optically controlled array antenna for transmission. SMF length L is 100, 70 and 50 m at f = 20, 30 and 40 GHz, respectively in Fig. 2(a) and 200, 130 and 100 m at 20, 30 and 40 GHz, respectively in Fig. 2(b). Microwave/millimeter-wave phases relative to the phase corresponding to λ_1 = 1559.79 nm are shown. Since both experimental and calculated phases are coincided very well, standard deviation of the obtained phase at each microwave/millimeter-wave frequency is shown in Table 1 to know the phase variation correctly. Although obtained phase deviation is slightly increased as microwave/millimeter-wave frequency is increased, phase deviation of less than 3 deg. at 40 GHz is realized.

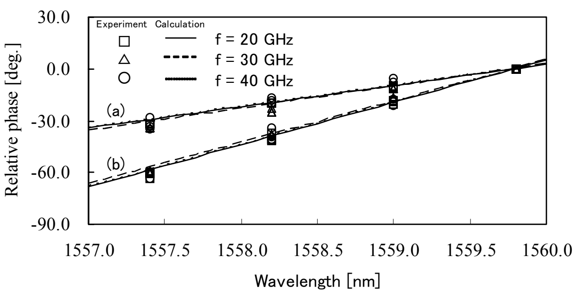

Fig. 2 Measured phase characteristics of 4-element optically controlled array antenna. (a) SMF length L = 100, 70 and 50 m at f = 20, 30 and 40 GHz, respectively. (b) L = 200, 130 and 100 m at f = 20, 30 and 40 GHz, respectively.

Table 1 Standard deviation of microwave/millimeter- wave phase at each frequency and wavelength.

	20 GHz L=100m	20 GHz L=200m	30 GHz L=70m	30 GHz L=130m	40 GHz L=50 m	40 GHz L=100m
λ_2	0.5 deg.	1.0 deg.	0.1 deg.	0.6 deg.	2.1 deg.	1.5 deg.
λ_3	0.1 deg.	1.9 deg.	1.0 deg.	0.8 deg.	1.3 deg.	2.7 deg.
λ_4	0.3 deg.	1.5 deg.	0.4 deg.	0.6 deg.	2.7 deg.	1.8 deg.

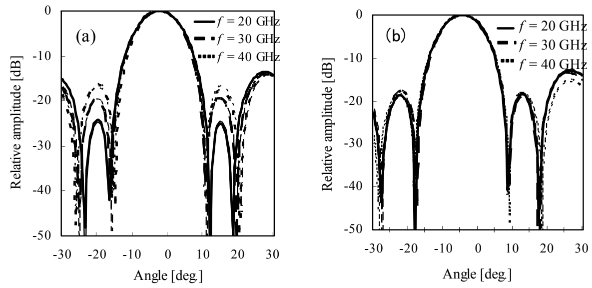

Fig. 3 Estimated radiation pattern of 4-element array antenna. (a) SMF length L = 100, 70 and 50 m at f = 20, 30 and 40 GHz, respectively. (b) L = 200, 130 and 100 m at f = 20, 30 and 40 GHz, respectively.

Radiation pattern of 4-element array antenna is estimated based on the measured 20 - 40 GHz phase characteristics and compared with calculated pattern in Figure 3. Thick line shows estimated pattern and thin line shows calculated one. Estimated beam scan angle is 2.5 and 4.5 deg. in Fig. 3(a) and (b), respectively at all the frequencies f = 20, 30 and 40 GHz. Well agreement of estimated pattern and calculated one clarifies accuracy of obtained phase characteristics.

4 Conclusion

20-40 GHz phase accuracy of 4-element WDM-based, true-time delay optically controlled array antenna was investigated. WDM-based microwave/millimeter-wave phase shifters composed of four DFB lasers and one SMF is experimentally verified. Measured 20 – 40 GHz phases are coincided well with calculated values and phase deviation of less than 3 deg. are realized independent of microwave/millimeter-wave frequencies.

References

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