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Photonic Approach to Beam Steering of Phased Array Antenna

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***Abstract*— Beam steering of phased array antenna was achieved by changing the wavelengths of tunable light sources, where RF power was transmitted to the array antenna through optical fibers with finite chromatic dispersion. A concept of photonic approach to beam steering was first explained and then experimental demonstrations were shown for a 2 GHz array antenna with 4 patch antenna elements and for a 20 GHz array antenna with 2 patch antenna elements. The relationships between the phase shift of the RF signal and the fiber length, chromatic dispersion, and the wavelength tuning range were verified through the experiments. Transmission penalty caused by the phase difference between the upper and lower sidebands due to the chromatic dispersion was also studied together with the beam steering capability as a function of RF frequency. It has been shown that this method is viable up to millimeter wave band, if we choose a proper length of fiber and a wavelength tuning range.**

I. INTRODUCTION

Phased array antennas with beam steering capability are attractive not only for sophisticated applications but also in terms of low power consumption in mobile and WiFi systems. Microwave photonics, i.e., RF power feeding through fiber, may give a solution to realize compact and light weight array antennas. Although some studies were attempted in the past [1][2], they did not look suitable for massive use in current radio systems. On the other hand when we consider recent advances in semiconductor tunable lasers[3][4] and high power photodiodes (PDs) [5], it seems to be right time to revisit the viability in order to realize really smart, i.e., compact, light weight, and cost effective array antennas which can be used in wide range of applications including macro, pico, and femto cells for advanced mobile systems and WiFi access points. This paper presents basic concept of photonic approach to beam steering of the phased array antennas and experimental results at 2 GHz and 20 GHz. The effect of chromatic dispersion on the RF transmission penalty arisen from the phase difference between the double sidebands in an amplitude-modulated optical signal is also shown.

II. BASIC CONCEPT OF PHOTONIC APPROACH TO RF PHASE SHIFT FOR BEAM STEERING

The proposed scheme for beam steering of array antennas is schematically shown in Fig. 1. Multiple wavelength optical signals emitted from tunable light sources (TLSs) covering different wavelength ranges are multiplexed by a wavelength division multiplexing (WDM) coupler or by an optical coupler. The multiple wavelength signals are simultaneously modulated by an RF signal in an optical intensity modulator. A single-mode fiber (SMF), which has a typical chromatic dispersion parameter D of 16-18 ps/nm/km at the wavelength of 1.5 μm band, generates relative time delays among the optical signals as shown in the figure.

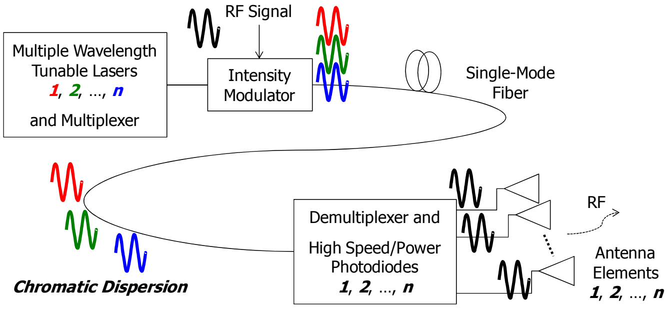

Fig. 1. Schematic illustration of RF beam steering of array antennas with multi-wavelength tunable lasers and fiber chromatic dispersion

After being demultiplexed to each wavelength, optical signals are converted to baseband RF signals via PDs. If we use multiple fibers for multiple wavelengths, the demultiplexer can be eliminated. The RF signals are fed to array antenna elements and form predefined radiation beam. By controlling the wavelengths of TLSs, the relative RF phase shifts can be varied due to fiber chromatic dispersion and thus the radiated RF beam is steered. In the present study, only the transmission with the direction from laser sources to the array antenna, in other words, only the RF down link is addressed.

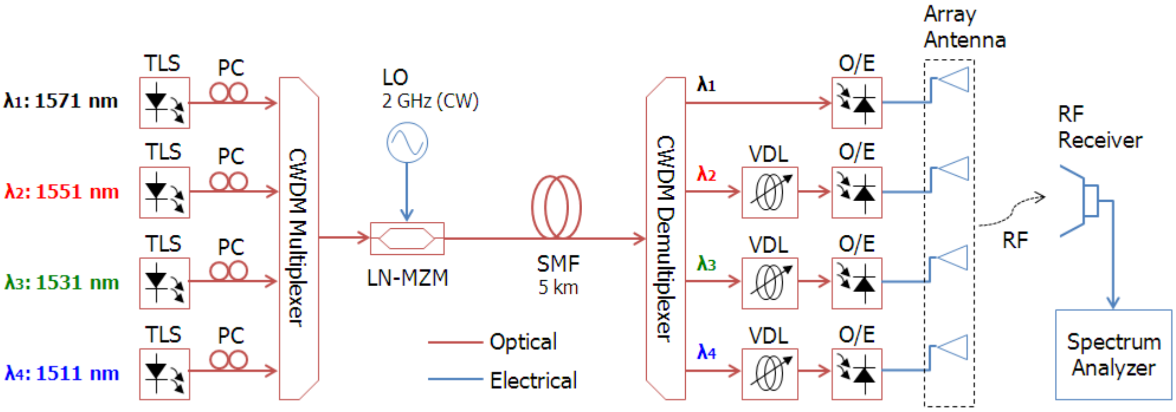

Fig. 2. Experimental setup for antenna beam steering demonstration

However, it should be noted that the technique would be also applicable to the RF uplink in a similar way and will be reported elsewhere.

The wavelength tuning range $\Delta\lambda$ in order to obtain π phase shift of RF signal is given by the following equation:

$$\Delta\lambda = {}^{1}\!/_{2LDf_{RF}} \qquad (1)$$

, where L is the length of transmission optical fiber and f_{RF} is the RF carrier frequency.

III. EXPERIMENTAL DEMONSTRATION

We used a normal SMF with a typical chromatic dispersion of D = 16-18 ps/nm/km. We assumed a wavelength tuning range of $\Delta\lambda$ = 2-3 nm, considering practical device performance of tunable semiconductor lasers for WDM optical fiber communications. The fiber length is determined from Eq. (1) depending on the RF frequency for the demonstration.

A. $f_{RF} = 2$ GHz

A SMF of L = 5 km was used, then $\Delta\lambda$ for π phase shift was 2.8 nm, assuming D = 18 ps/nm/km. Figure 2 shows the beam steering experimental setup. Four wavelengths emitted from the TLSs were initially set to λ_1 = 1571 nm, λ_2 = 1551 nm, λ_3 = 1531nm and λ_4 = 1511 nm, and their outputs were polarization-controlled (PC) and combined by a coarse WDM (CWDM) multiplexer. The multiplexed optical signals were simultaneously modulated in a Lithium Niobate Mach-Zehnder modulator (LN-MZM) driven by a 2 GHz continuous wave (CW) RF signal generated by a local oscillator (LO). After transmission through 5 km-long SMF, four optical signals with different wavelengths were divided by a CWDM demultiplexer, and converted to electrical RF signals by optical-to-electrical (O/E) converters which were composed of PDs and RF amplifiers[1]. Variable optical delay lines (VDLs) were inserted in order to adjust the initial phase offsets among RF signals before being O/E converted and then fed to the four array antenna elements. If we make such an offset adjustment so that the phases and the amplitudes of four RF signals are the same, a single beam toward the straight forward direction is formed. The actual antenna beam patterns were measured by rotating the array antenna with the fixed RF receiver. Whole experimental setup was installed in an anechoic chamber to exclude unintentional interference by reflected or external signals.

The array antenna used in this experiment was comprised of four patch antennas in 2 GHz band as shown in Fig. 3. Each patch antenna was separated by about 63 mm from each neighbor, which corresponds to 0.42 λ_{RF}.

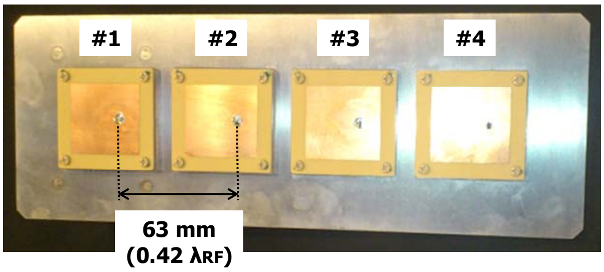

Fig. 3. Arrayed patch antennas for 2 GHz band

Prior to the beam pattern measurement it was confirmed by directly monitoring the waveforms at the antenna input points that the phases of all four RF signals were the same. By changing the wavelengths of λ_2 and λ_4 with 3 nm toward the longer wavelength side, π phase shifts of the two RF signals were induced. Taking into account the result, the actual value of D is calculated to be 16.7 ps/nm/km.

Figs. 4 (a) and (b) show the measured beam patterns in cases of the phase shift of 0 and π. It is seen that the peak of the beam form appears at the observation angle of 0 degree in the case of the phase shift of 0, while a null point of the beam form appears at the same observation point in the case of the phase shift of π. The numerically calculated results were also plotted in the figure, which are derived from the array factor expressed as

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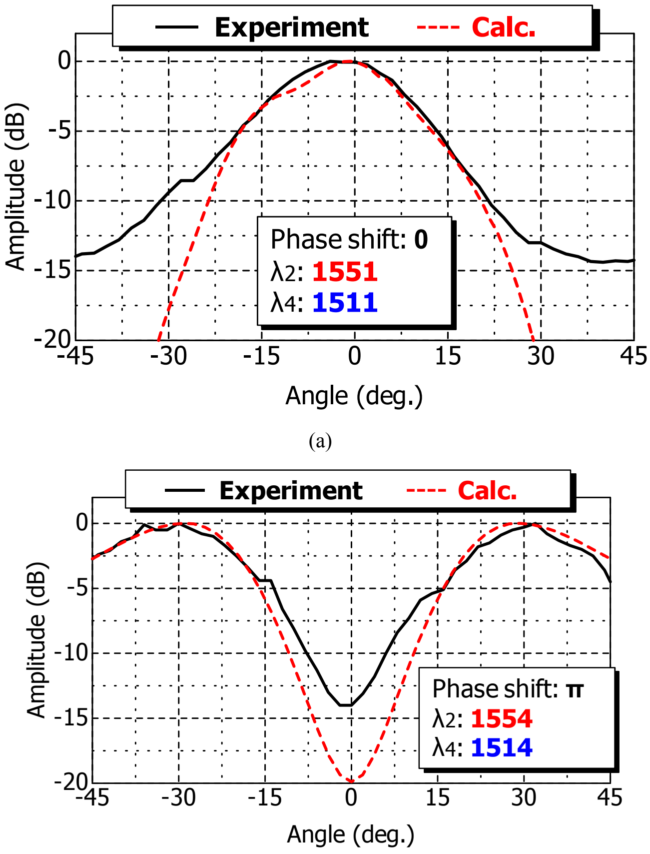
[1] Considering recent development status of high output-power and/or high speed PDs [5], it is expected that RF signals from such PDs may be able to directly drive the antenna elements without RF amplifiers.

$$\sum_{k=1}^{4} \exp\left(-j \frac{2\pi}{\lambda_{RF}} d_k \sin\theta + \beta_k \right) \tag{2}$$

where d_k is the separation between the antenna elements, θ is the observation angle, and β_k is the phase shift among input RF signals to the array antenna as illustrated in Fig. 5. The difference between the experiments and the numerical calculations in the smaller amplitude region (<-10 dB) may be attributed to the insufficient optical received power. However, we think that the proposed antenna beam steering scheme utilizing the fiber chromatic dispersions was successfully demonstrated.



(a)

(b)

Fig. 4. Measured antenna beam patterns obtained for f_{RF}= 2 GHz in cases of the phase shift of (a): 0 and (b): π

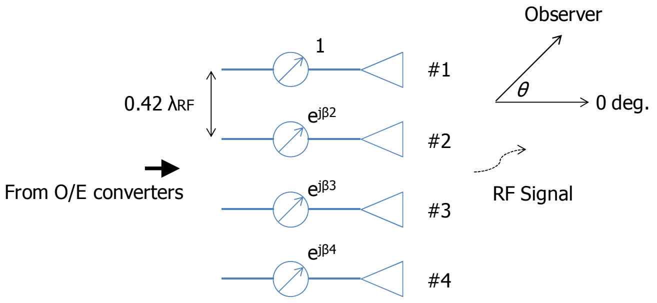


Fig. 5. Schematic illustration of four array factors with the phase shifts

B. f_{RF} = 20 GHz

Now both the fiber length and the wavelength tuning range were reduced to L = 1 km and $\Delta\lambda$ = 1.5 nm. The experimental setup was similar to A (f_{RF} = 2 GHz) and is shown in Fig. 6.

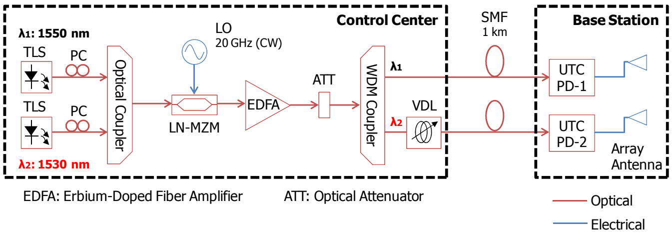


Fig. 6. Experimental setup for f_{RF} = 20 GHz

UTC-PD denotes Uni-Traveling Carrier Photo-Diode [6], which are assumed to operate up to millimeter wave band. The UTC-PDs directly drive the patch antennas in this case and the antenna site, assuming a base station in a mobile system, is much simpler. Because of the availability of UTC-PDs, experiments for two antenna elements were conducted as shown. Moreover the UTC-PD output was connector-ended, and therefore the separation between the two patch antennas was as large as an RF wavelength (λ_{RF} = 15 mm).

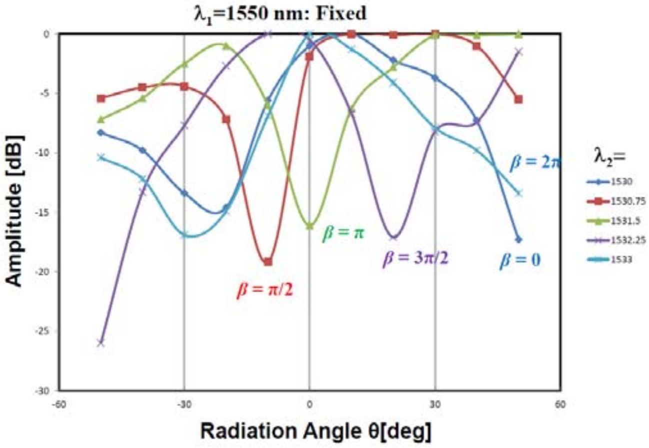


Fig. 7. Beam patterns obtained for f_{RF}= 20 GHz, where the RF phase difference β between the two wavelengths was changed from 0 to 2π.

Obtained beam patterns are shown in Fig. 7. λ_1 was fixed to be 1550 nm, while λ_2 was changed from 1530 to 1533 nm. The 3 nm change corresponded to the RF phase shift of 2π. Because of an imperfection in the patch antenna, the radiated beams are slightly deformed compared to the results of 2 GHz demonstration but the beam steering function is clearly manifested.

IV. TRANSMISSION PENALTY DUE TO RELATIVE PHASE DIFFERENCE BETWEEN DOUBLE SIDEBANDS

While the fiber chromatic dispersion is useful for phase shift generation to steer the beam from array antenna as demonstrated above, an unwanted effect is also induced. Figure 8 shows a schematic illustration of a spectrum of the optical signal that is amplitude-modulated by an RF signal. By neglecting higher-order terms, the optical spectrum of the amplitude-modulated signals consists of an optical carrier at the central wavelength of λ_0 and double sidebands which are respectively separated by the RF carrier frequency of f_{RF} from λ_0. Fiber chromatic dispersions induce the relative phase shift between the double sidebands, which may result in decrease in the amplitude modulation index and such a decrease is regarded as "transmission penalty". The RF output power P_{RF} considering the phase shift between double sidebands is given by the following equation:

$$P_{RF} \propto \cos^2\left(\frac{\pi L D \lambda_0^{\,2} f_{RF}^{\,2}}{c}\right) \qquad (3)$$

, where c is the velocity of light in the optical fiber [7,8]. As is easily seen from Eq. (3), the RF output power P_{RF} decreases with the increase of the phase shift of φ, which is the argument of cosine function on the right hand side, because the double sidebands start to destructively interfere with each other and they cancel out when φ reaches π.

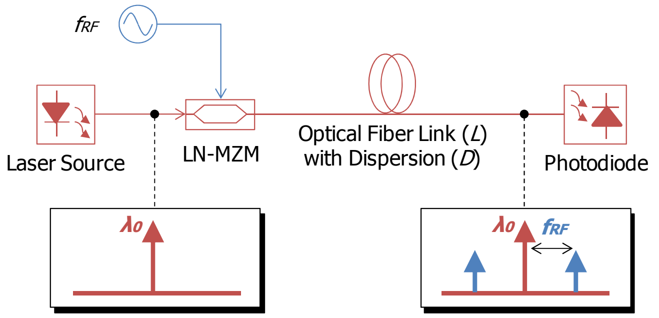


Fig. 8. Schematic illustration of an optical spectrum amplitude-modulated by RF signals

The blue lines in Fig. 9 show the fiber length requiring π phase shift for the given $\Delta\lambda$, which are derived from Eq. (1). The two red points show the experiments described above. The green lines indicate the relationship between the fiber length and f_{RF}, where the transmission penalty, i.e., the decrease of the RF modulation according to Eq. (3) is less than 1 dB and 3 dB below the lines. The result indicates that the transmission penalty for a lower f_{RF} such as 2 GHz is negligible even after transmission through a 100 km-long fiber. On the other hand, for the higher frequencies, the blue lines and green lines come closer and at millimeter-wave band such as 60 GHz, it seems that the wavelength tuning range larger than 3 nm is required in order to avoid the penalty.

V. CONCLUSIONS

Photonic approach to beam steering of phased array antenna was presented, where the fiber chromatic dispersion effects were utilized. A straight forward effect is to change the phase of RF signal by changing the wavelength which carries the RF signal to each array element. The other effect is RF transmission penalty arising from the phase shift between double sidebands of amplitude-modulated signal. The penalty should be negligible in the microwave band up to 10 GHz but it should be taken into account in the mm-wave band, for example, 60GHz.

When we consider recent advancement in manufacturing process of InP-based tunable laser diodes together with high power and high speed PDs, we may be able to pioneer a new type of flexible and smart mobile radio antenna systems.

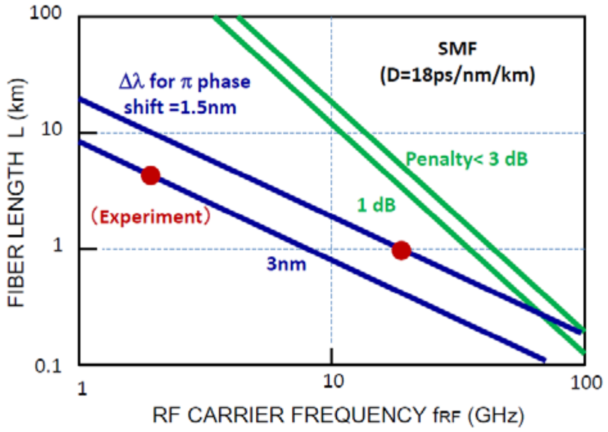


Fig. 9. Fiber length as a function of RF carrier frequency for the penalty due to dispersion between double sidebands (green lines) and giving π phase shift (blue lines).

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