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MULTIBEAM OPTICAL SIGNAL PROCESSING ARRAY ANTENNA USING OPTICAL WAVEGUIDE ARRAYS AND LENS

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I. INTRODUCTION

Phased array antennas are expected to be effective for use in advanced wireless communications for mobile radio communication, wireless LAN, and satellite communication [1]. Recently, the application of photonics technology to microwave array antennas has been studied [2-5]. An optically controlled phased array antenna is very well-suited for fiber-optic microwave or millimeter-wave links. Optical components such as a lens and optical fibers can be combined to form a beam forming network (BFN) using the spatial optical signal processing (OSP) method. In addition, a high-quality RF signal can be generated from the frequency offset between the lights by using a heterodyne technique. By using a Fourier transform (FT) lens, beam scanning and beam forming can be carried out by simply arranging the light source in the front focal plane of the FT lens. ATR has proposed a variety of functions for OSP-BFNs, such as beam shaping, beam scanning, and multibeam formation [2]; we have experimentally demonstrated the achievements of beam steering and multibeam formation in the Ku-band [3]. However, these OSP-BFNs mainly consist of optical fibers, so they have some problems with miniaturization and stability. Furthermore, the use of light in OSP-BFNs is inefficient because the area of the core is quite small compared with the clad of the optical fiber. NTT uses a slab waveguide and has confirmed the OSP-BFN function [4]. An optical waveguide would greatly reduce the light transmission loss, the size of the optical processing feed part, and the optical alignment difficulties. A two-dimensional beam forming method using only a slab-waveguide was proposed [5], however, the relationship of the light and the RF beam direction is difficult to determine.

We applied optical waveguide arrays and a micro lens to the emitting and sampling of laser light parts in an OSP-BFN in order to solve the above mentioned problems. In the case of this structure, if a multi-layered waveguide arrays are applied, a two-dimensional OSP-BFN can be easily constructed. In this report, we describe the design concept of a one-dimensional OSP-BFN using waveguide arrays, and show the system, which we constructed. The efficiency of an OSP array antenna system, which including an optical RF sources, an OSP-BFN, and a linear array antenna, was demonstrated in experiments on multibeam formation in the X-band.

II. SYSTEM CONFIGURATIONS

The schematic diagram of the OSP microwave or millimeter-wave array antenna system for multibeam formation is shown in Figure 1. For example, two lights whose frequency difference is f_1 are emitted from different positions to the space at the front focal plane of the FT lens. They are transmitted through the FT lens, and are sampled at a back focal plane. The RF signals, whose frequency is f_1, with a phase

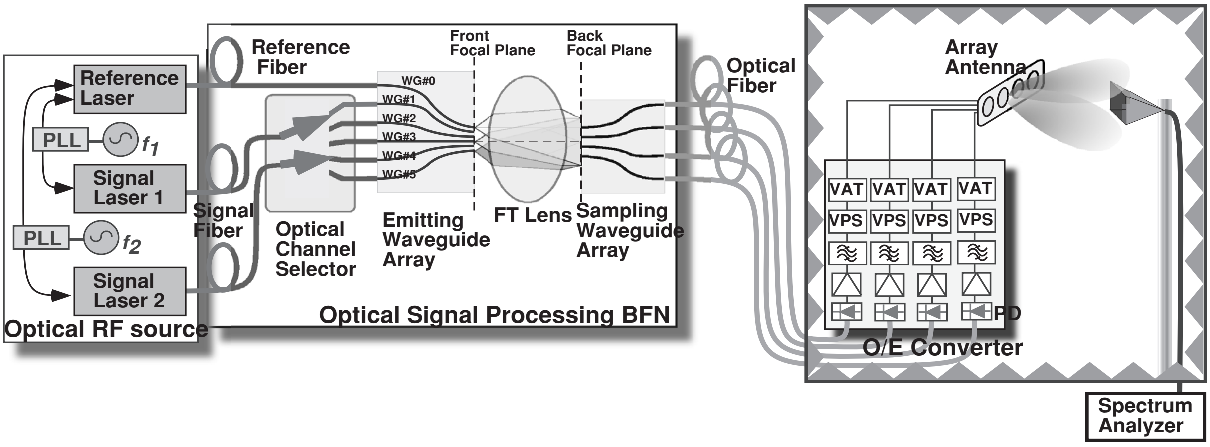


Figure 1: Diagram of the optical signal processing array antenna

shift determined by the incident of the light angles, can be detected by photodetectors (PDs). These RF signals are fed to each element of the array antenna, and RF radiation beam control is carried out. This system mainly consists of the following three parts.

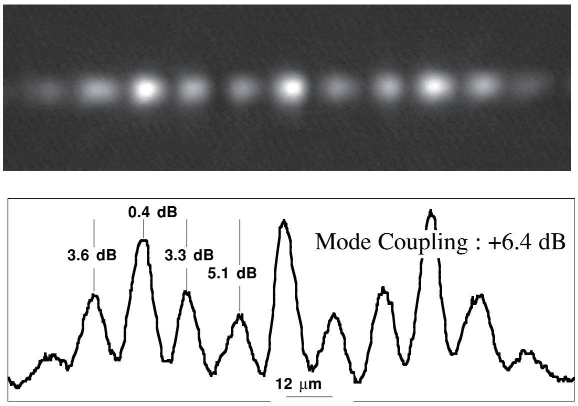
The optical microwave or millimeter-wave RF source: In this part, LD-pumped Nd:YAG ring lasers operating at a wavelength of 1.319 µm (227 THz) are used as signal and reference lasers. The frequency difference between them is phase-locked to a RF synthesizer by controlling the temperature and strain of the laser crystals. Furthermore, we can generate many RF signals simultaneously by adding signal lasers that phase-lock to the reference laser.

The OSP-BFN: This part consists of the FT lens, and the emitting and sampling waveguide arrays. These waveguide arrays are placed at the front and back focal plane, respectively, of the FT lens. Each laser is connected to a port of the emitting optical waveguide array. The lights from the lasers are emitted into the space, then are transmitted with the FT lens, and are incident onto the sampling waveguide array. When these lights are transmitted through the FT lens, they are Fourier transformed. The emitted position of the light corresponds to the phase distribution of the interference excitation field in the sampling plane. The design parameters of the OSP-BFN are described the next section.

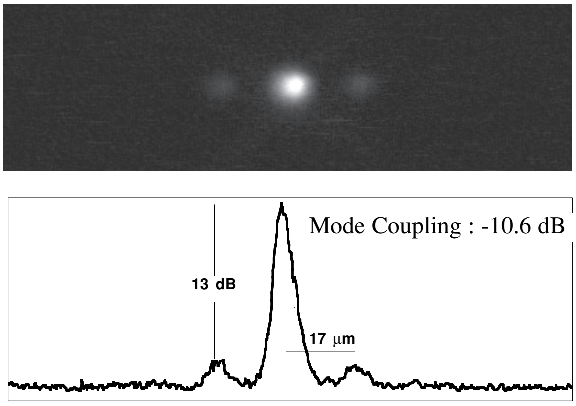
O/E conversion and the array antenna: The O/E conversion part is located near the array antenna in the anechoic chamber, and connected to the OSP-BFN part with optical fibers. These lights from the OSP-BFN are photoelectrically converted to beat the RF frequency signal by PD, and are then fed to an array antenna. The array antenna is for X-band frequencies, a 0.6-wavelength-spaced four-element linear array antenna, and each element is a circular patch antenna. The variable phase shifters adjust the phase errors resulting from the different optical fiber lengths.

III. OSP-BFN Design

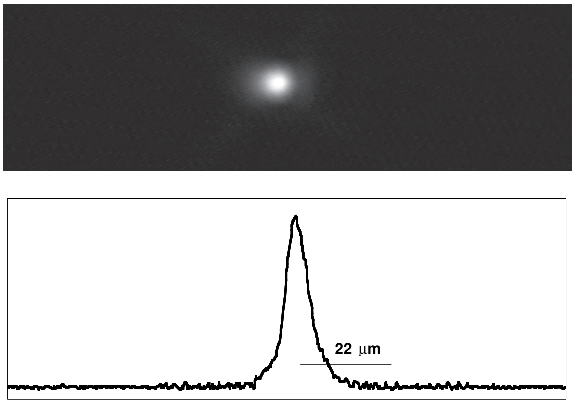
Sampling Waveguide Array: In order to reduce optical loss in the OSP-BFN, the ratio of the core region to the clad (fill factor) must be raised in the sampling plane. Therefore, it is desirable for the adjacency core interval to be narrow. However, it cannot be brought too close to the adjacency core because this would cause mode-coupling to occur in them. In order to investigate this mode-coupling, we trial manufactured three kinds of SiO_2 slab-waveguide arrays, with core intervals of 12, 17, and 22 µm, and a spot size of 8 x 8 µm in Gaussian profile. The measured near field pattern (NFP) light input for one waveguide of each waveguide array is shown in Figure 2. Here, mode-coupling values are defined as the ratio of the total power of non-input waveguides to the input waveguide output. From Figure 2, it can be seen that mode-coupling with the waveguide having a core interval of 12 µm is very high, rendering it useless. Therefore, we used a waveguide with a core interval of 17 µm, whose mode-coupling is below 10 dB, as the sampling waveguide array.



(a) interval is 12 µm



(b) interval is 17 µm



(c) interval is 22 µm

Figure. 2 Measured NFP of each waveguide

Emitting Waveguide Array: Because the mode-coupling of the waveguide array with a 22 µm interval was low, we used it for emission. The variation of in the insertion losses of every port of the sampling and emitting waveguides are shown in Figure 3. As this figure shows, the losses are uniform within 0.2 dB of the standard deviation.

FT lens: From the well-known Shift Theorem of the FT lens, a spatial change in the field in the focal plane of one side introduces a linear phase shift in the focal plane of another side. After transmission through the FT lens, the Gaussian beams will keep the Gaussian mode unchanged. The spot size ω_l in the sampling plane is given by $\omega_l=\lambda F/\pi\omega_0$, where ω_0 is the spot size of the emitting waveguide, F is the focal length of the FT lens, and λ is the wavelength of the lasers. In this manner, when the F is short, the ω_l becomes low, and the light concentrates on the neighborhood of the optical axis. The ideal value of the F is different according to the element number of the antenna, that is, the element number of the sampling waveguide. Here, a four-element array antenna is assumed, and the overall width of the four-element sampling waveguide becomes 59 µm. Therefore, it is desirable that the F is longer than 1.1 mm in order to make the ω_l larger than 59 µm so the light beam can cover the sampling waveguide. Here, we used a 0.25-pitch gradient index (GRIN) micro lens. This 0.25-pitch lens collimates the point source. Its F is 1.92 mm. Then, the spot size at the sampling focal plane becomes 101 µm in a Gaussian profile. Each front and back focal plane is located in each end of the lens, so the optical alignment becomes easy. Table 1 shows a summary of each parameter of these OSP-BFN components, such as the waveguides and lens.

IV. MEASUREMENT RESULTS

Two signal lasers, 1 and 2, were phase-locked to a reference laser with a different RF frequency offset. The reference laser was connected to port #0 of the emitting waveguide, and signal lasers 1 and 2 were each independently connected to the port from #1 to #5. The three laser lights were emitted into space, transmitted through the lens, mixed together spatially, and then sampled by the waveguide array. Each laser's optical power into the emitting waveguide was +12 dBm.

The spectra for the antenna reception of relatively high levels of two RF signals (in the X-band with a 100 MHz frequency difference between the two RF signals) are shown in Figure 2. The optical output of each sampling waveguide was improved 22 dB compared with our earlier report using a sampling optical fiber array [3]. This improvement value is equivalent to 44 dB with an electrical signal after square-law detection. In this experiment, when the signal laser was connected to port #1 of the emitting waveguide, we adjusted to steer the main beam to the front direction. In Figure 2, signals 1 and 2 were connected to ports #1 and #3, respectively. This figure shows that multiple frequency RF signals can be generated.

Figure 3 shows the measured far-field radiation patterns of the OSP array antenna. We changed the connection port with the signal lasers from #1 to #5 by using an optical channel selector. Each line represents the port number of the waveguide connected to the signal laser. By changing the port, the radiation pattern of the optical beam in the OSP-BFN is changed, and the phase distribution of the RF feeding signal is tilted. The direction of the main beam was steered by changing the port of the waveguide, and the expected radiation directions were achieved. Furthermore, we can miniaturize the OSP-BFN part by applying optical waveguide arrays and a GRIN micro lens.

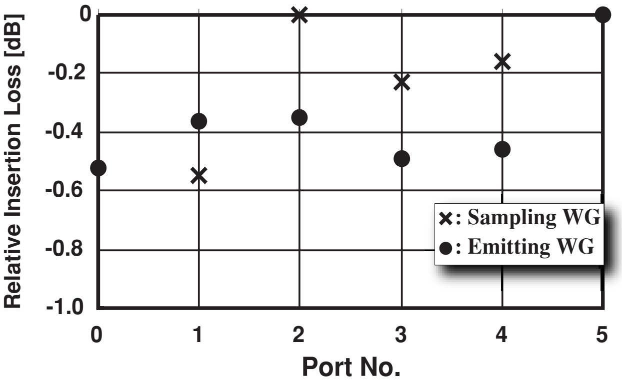


Figure. 3 Insertion losses of waveguides.

Table 1: Designed parameters of OSP-BFN components

Parameter		Value
Wavelength		1.319 µm
Emitting waveguide array	Core size	8 X 8 µm
	Core interval	22 µm
Sampling waveguide array	Core size	8 X 8 µm
	Core interval	17 µm
Lens (GRIN micro lens)	Pitch	0.25
	Focal length	1.92 mm
	Length	4.8 mm
	Diameter	1.8 mm
	N.A.	0.46
Spot size at back focal plane	ω_l	101 µm

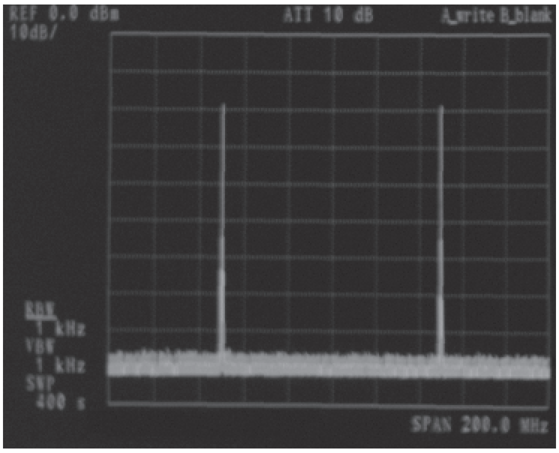


Figure 4: Spectra of two RF signals (X-band) from antenna reception.

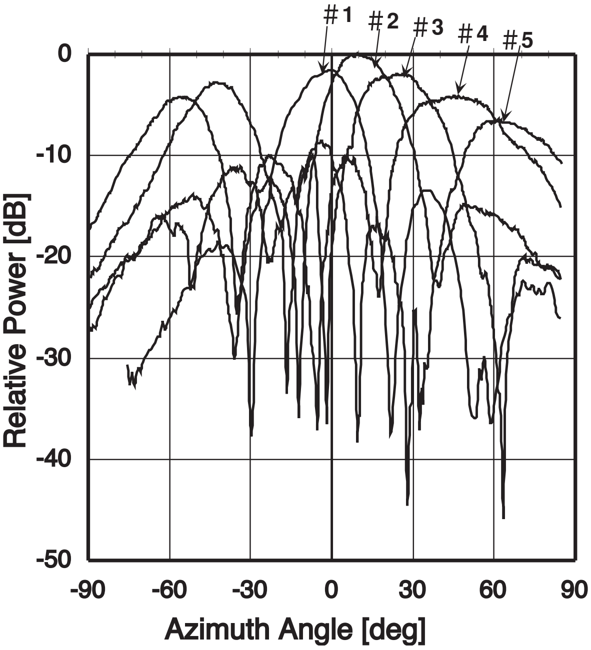


Figure 5: Measured far-field radiation patterns of the optical signal processing array antenna.

V. CONCLUSIONS

We built an X-band OSP phased array antenna system including an optical RF source, an OSP-BFN, and a linear array antenna. In the OSP-BFN, we used optical waveguide arrays and a GRIN micro lens in order to reduce the light transmission loss, the size of the optical processing feed part, and the optical alignment difficulties. The core interval of the sampling waveguide array must be narrow in order to improve optical power. A waveguide with a core interval of 17 μm was used, and its mode-coupling between the adjacency core was below −10 dB. A GRIN micro lens, with a pitch of 0.25 and a focal length of 1.92 mm, was used, so the spot size at the sampling plane could cover the sampling waveguide area, and the optical alignment could be easily made. We demonstrated multiple RF beam formation with the phased array antenna in the X-band.

The feasibility of the OSP-BFN is confirmed. If we employ a multi-layered waveguide array as an OSP-BFN, a two-dimensional multibeam array antenna can be easily constructed.

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