Two-Dimensional Optical Signal-Processing Beamformer Using Multilayer Polymeric Optical Waveguide Arrays

Tomohiro Akiyama, *Member, IEEE*, Keizo Inagaki, *Member, IEEE*, Takashi Ohira, *Senior Member, IEEE*, and Makoto Hikita

***Abstract*—Optically controlled beamforming techniques are very effective for phased-array antenna control. We have developed a two-dimensional (2-D) Fourier transform optical signal-processing (OSP) beamformer. In the OSP beamformer, we use multilayer polymeric optical waveguide arrays to generate and control a 2-D specific phase-front and sample 2-D distributed light beams. These multilayer optical waveguide arrays consist of three layers and 13 waveguides; each layer has four, five, and four waveguides, respectively. We experimentally demonstrate 2-D beam steering in the X-band, and show the feasibility of the 2-D OSP beamformer.**

***Index Terms*—Beamforming network, microwave photonics, multilayer optical waveguide array, optically controlled array antenna, optical signal processing, polymeric optical waveguide.**

I. Introduction

IN ADVANCED wireless communications, such as the next-generation satellite communications, mobile radio communications, and wireless local area networks (LANs), phased-array antennas are expected to be effectively utilized and beamforming techniques for phased-array antennas are expected to become more important. Optically controlled phased-array antennas have become very attractive because they offer advantages such as a wide bandwidth, a lightweight and small-sized circuit, low transmission losses, and no electromagnetic interference. Various kinds of research on the optical control of array antennas have been encouraged by various organizations [1]–[4].

Optical heterodyne techniques can control the phase of microwave signals by controlling the phases of lightwaves, thereby reducing the beamformer size requirement. Moreover, by utilizing a spatial Fourier transform (FT) optical signal-processing (OSP) function of the FT lens, many phases of the lightwaves can be controlled simultaneously, and this function can substitute for a number of microwave components in conventional beamformers. OSP beamforming networks (BFNs) combine an optical heterodyne technique and an FT function of the optical lens; the original concept was proposed in [5]. Due to their simplicity by substituting a number of microwave components for a simple optics, OSP–BFNs are expected to play an important role in future wide-band wireless communications, especially in future satellite communications with a large number of microwave or millimeter-wave beams and antenna elements [3]. A variety of functions such as beam shaping [6], one-dimensional beam scanning [7], multibeam transmission [8] and reception [9], and frequency independency [10] have been proposed and experimentally demonstrated. These OSP–BFNs mainly consist of optical fiber arrays. Concerning two-dimensional (2-D) OSP–BFNs, there is a report using a 2-D optical fiber array. However, the fabrication process of the 2-D optical fiber array arranges the optical fibers two-dimensionally, and then fastens the optical fibers with glue, after they have been bundled up manually. Therefore, the process has large production errors, is not suitable for mass production, and has a production cost that is difficult to reduce.

In order to miniaturize and mechanically stabilize OSP–BFNs, integration on optical waveguides has been found to be effective [11], [12]. An optical waveguide array can greatly reduce the size of the optical processing part, optical alignment difficulties, and optical insertion losses. 2-D beam control requires the arrangement with 2-D optical waveguide arrays. However, all of the optical waveguide arrays reported up to now have been single layered. Ogawa *et al.* proposed a 2-D beamforming method using only a slab waveguide [13]. However, their method implements the grating lobes to the 2-D beam formation. Therefore, it is difficult to determine the relationship between the light and the microwave beam direction.

In order to solve the above problems, we fabricated polymeric multilayer optical waveguide arrays [14], [15], which are the key components for achieving a 2-D OSP–BFN, and developed a 2-D OSP–BFN. The applications of these arrays made 2-D microwave beam control possible. The optical waveguide array pattern can be fabricated by photolithography, and the thickness of each layer can be controlled by spin-coating technology. Therefore, we can expect high precision, mass production capability, and fabrication cost reduction.

This paper first briefly introduces the principle of an OSP–BFN, describes characteristics of a multilayer optical waveguide array, which is a key component for achieving a 2-D OSP–BFN, and shows fundamental characteristics of a developed 2-D OSP–BFN. Finally, we describe results from an experiment on 2-D beam scanning at the X-band using the 2-D OSP–BFN.

Manuscript received January 5, 2001; revised June 11, 2001.

T. Akiyama was with ATR Adaptive Communications Research Laboratories, Kyoto 619-0288, Japan. He is now with the Mitsubishi Electric Corporation, Kanagawa 247-8501, Japan.

K. Inagaki and T. Ohira are with ATR Adaptive Communications Research Laboratories, Kyoto 619-0288, Japan.

M. Hikita is with the NTT Advanced Technology Corporation, Tokai, Ibaraki-ken 319-1193, Japan.

Publisher Item Identifier S 0018-9480(01)08702-6.

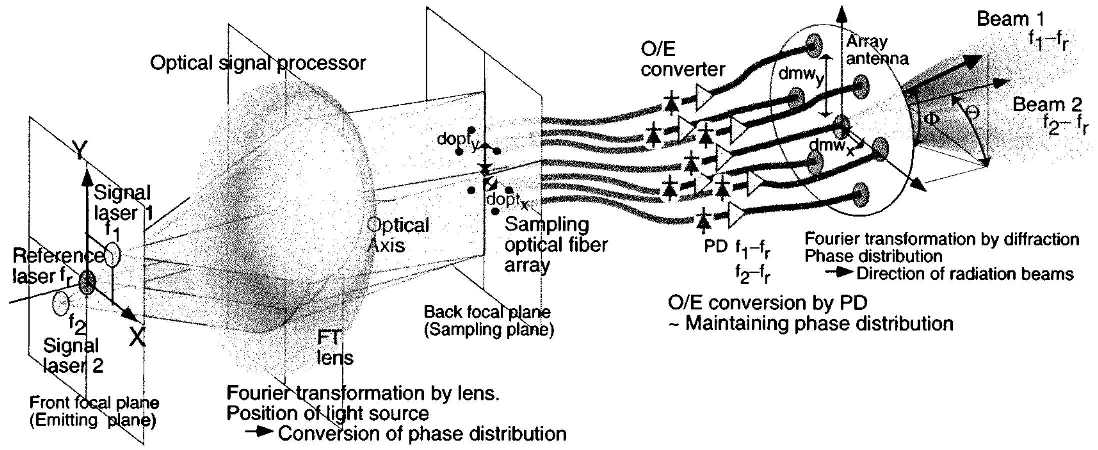

Fig. 1. Schematic diagram of an OSP array antenna for transmission.

II. Principle of and OSP Array Antenna

In this section, we briefly explain the principle of the OSP array antenna. Fig. 1 shows a schematic diagram of an OSP multibeam array antenna for transmission. In this figure, an FT lens is employed in the spatial parallel optical signal processor and produces a large number of multiple microwave beams. The light beams are emitted from the reference laser and signal lasers, which are set on the front focal plane of the FT lens. These light beams are incident on the FT lens, and are Fourier transformed. The light beams are combined and sampled spatially by an optical fiber array that is set on the back focal plane of the FT lens. A photodiode (PD) is connected to the end of each optical fiber. Each PD generates microwave signals by heterodyne detection; the frequency is the frequency difference between the reference and signal lasers. This microwave signal is fed to each antenna element. The phase of the lightwave on the sampling plane is controlled by moving the lasers, and is then transferred to the antenna array. The emitting position of the signal lasers corresponds to the beam direction from the array antenna. The relation between microwave beam direction (Θ, Φ) from the array antenna and signal laser-emitting position (X, Y) can be expressed by [7]

$$\sin\Theta = \frac{d_{\mathrm{opt}_x}/\lambda_{\mathrm{opt}}}{d_{mw_x}/\lambda_{mw_x}}\,\frac{X}{f} \qquad \sin\Phi = \frac{d_{\mathrm{opt}_y}/\lambda_{\mathrm{opt}}}{d_{mw_y}/\lambda_{mw_y}}\,\frac{Y}{f} \tag{1}$$

where d_{opt_x}, d_{opt_y} denotes the element spacing of the sampling optical fiber or waveguide array, d_{mw_x}, d_{mw_y} denotes the element spacing of antenna elements, the subscripts x and y represent the horizontal and vertical directions, respectively, f is the focal length of the FT lens, λ_{opt} is the optical wavelength, and λ_{mw} is the microwave frequency wavelength. Optical heterodyne techniques, including an OSP–BFN, can control microwave phase shifting in independence of the microwave frequency, however, they cannot control the time delays of microwave signals. The OPS-BFN technique is not a true-time delay (TTD) beamformer. Therefore, OSP–BFN can operate any frequency range, but a bandwidth is limited with fixed antenna element spacing, as expressed in (1), which is the same as the conventional microwave phased arrays.

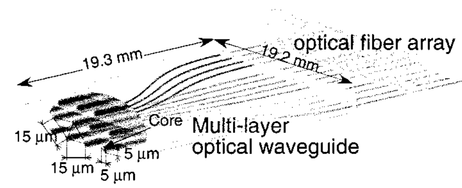

Fig. 2. Schematic diagram of multilayer optical waveguide array and fiber array.

This technique requires two frequency-offset optical beams, which can be fed from the same laser source or from two phase-locked laser sources. If we use many signal lasers, and each laser's frequency difference with the reference laser is set to the desired microwave frequency, the multiple microwave beams are generated individually, as shown in Fig. 1.

III. Polymeric Multilayer Optical Waveguide Array

An OSP–BFN uses a spatial OSP by the Fourier transformation of the FT lens. Accordingly, in order to control radiation beams two-dimensionally, a technique of controlling the emitting position on a 2-D plane is necessary. It is also necessary to arrange the sampling waveguide array on the sampling plane to be similar in figure to the arrangement of the 2-D microwave array antenna. Therefore, the optical waveguide array, which has a single layer, is made multilayered, and the one-dimensional emission and sampling lines are expanded two-dimensionally on a 2-D plane. In this section, we describe fabricated multilayer polymeric optical waveguide arrays.

We fabricated multilayer optical waveguide arrays, i.e., three-layer optical waveguide arrays, as shown in Fig. 2. The number of waveguides is 13; each layer has four, five, and four waveguides, respectively. We fabricated two multilayer optical waveguide arrays, one connected with lasers for light emission, and the other connected with PDs for sampling. With these arrays, the light-emitting position on the 2-D plane can be changed by selecting a connected port of the emitting waveguide with the lasers. The arrangement of each end face of the multilayer optical waveguide array for sampling is similar to the arrangement of the 2-D microwave array antenna elements. The light beam is

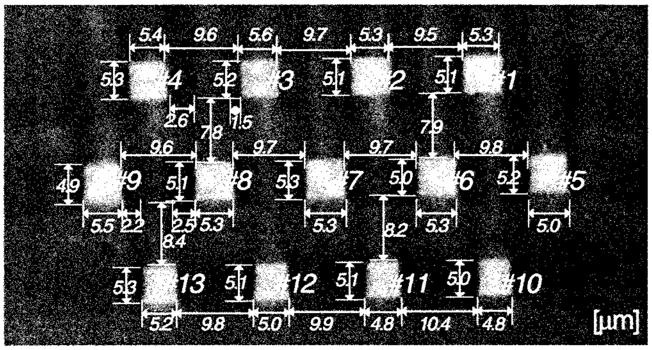

Fig. 3. Cross section of fabricated multilayer optical waveguide array.

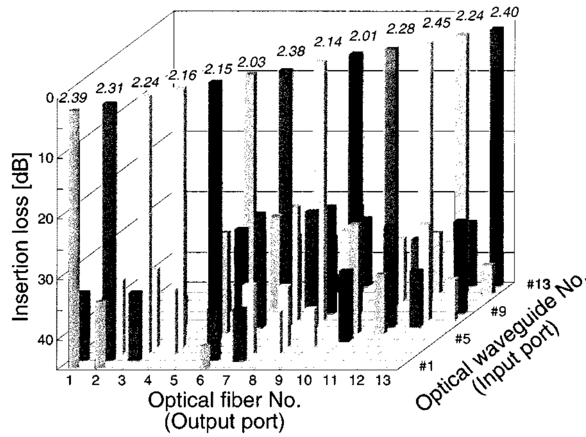

Fig. 4. Insertion losses of optical waveguides and crosstalk in optical waveguide array for sampling. Optical input to waveguide/output from optical fiber.

sampled by the optical waveguide, photoelectrically converted by the PD, and fed to each element of the 2-D array antenna.

The material of the optical waveguide arrays is polymer [14], [15] because polymer easily enables flat layers. The core is deuterated-polymethylmethacrylate (*d*-PMMA), the clad is UV-cured resin, and the refractive index difference Δn is 1% at a wavelength of 1.3 μm. Fig. 3 shows the photograph of a cross section of a fabricated multilayer optical waveguide array. The waveguide array chip size is 19.2 $\times$ 19.3 mm. The designed core size is 5 $\times$ 5 μm, the arrangement of the core is in a regular triangular lattice, and the waveguide pitch is 15 μm in the horizontal direction and $15\sqrt{3}/2$ in the vertical direction. As this figure shows, waveguides can be fabricated as designed, and every layer is flat. In the following section, each waveguide is numbered, as shown in Fig. 3 by " #."

Optical fiber is connected to one side of the waveguide arrays. To prevent the optical fiber from interfering with each other, the optical waveguide is spread by a curve, as shown in Fig. 2. Moreover, the height of each layer is different. Therefore, three optical fiber arrays, each consisting of four, five, and four pieces of optical fiber, respectively, are provided, in order to adjust the height of each waveguide layer to each optical fiber array with a precision of micrometer order. A polarization maintaining fiber (PMF) is connected to the emitting waveguide array in order to suppress degradation of the heterodyne detection efficiency. The sampling waveguide is connected to a standard single-mode fiber (SMF).

The average spot size, determined as the full width at $1/e^2$ of the maximum value, of 26 waveguides in the two multilayer optical waveguide arrays is 7.5 μm (horizontal) $\times$ 8.2 μm (vertical), and the standard deviations are 0.20 and 0.16 μm, respectively. All of the waveguides are single-mode excited.

Fig. 4 shows measurement results of insertion losses of each waveguide and the crosstalk in the waveguide array for sampling. Each measured value is the output light power from each optical fiber against the input light power into each waveguide end. Any output value of the fiber that differs from the light input waveguide is crosstalk. A large output value denotes a small crosstalk. The average insertion loss of each waveguide was approximately 2.2 dB, and the crosstalk in the waveguide array was almost greater than 30 dB. These insertion losses included the propagation loss of the waveguide and the coupling loss between the waveguide and fiber.

IV. 2-D Beam Steering Using Multilayer Optical Waveguide Arrays

The experimental setup of the transmission mode of the 2-D OSP array antenna is shown in Fig. 5. This system mainly consists of an optical microwave source, optical signal processor, opto-electronic (O/E) converter, and array antenna.

In the optical microwave source part, two LD-pumped ND:YAG ring lasers operating at a wavelength of 1.319 μm (227 THz) are used as the signal and reference lasers. The frequency offset between them is phase locked to a microwave synthesizer by controlling the temperature and strain of the laser crystals. If we want multiple microwaves, they can be generated by adding plural signal lasers that are phase locked to the reference laser.

The O/E converter is located beside the array antenna in an anechoic chamber, and connected to the OSP with single-mode optical fiber. The light from the OSP is photoelectrically converted to beat the microwave frequency signal by a PD, and is then fed to each element of the array antenna. Although Fig. 5 does not illustrate variable phase shifters and variable attenuators, they are connected between the preamplifier and antenna to calibrate the different optical fiber lengths and nonuniform PD responsivities.

In the following, the optical characteristic of the 2-D OSP–BFN is described as follows, and the measured 2-D microwave phase control and beam-steering results are described.

A. Optical Coupling Coefficiency

We assume the use of a 2-D array antenna with three rows of seven elements $(2+3+2)$, all arranged in a regular triangular lattice, as shown in Fig. 5. The 2-D OSP consists of an FT lens and two multilayer optical waveguide arrays for emitting the light beams and for sampling the beams. These optical waveguide arrays are located on the front and back focal planes of the FT lens.

From the well-known shift theorem for the FT lens, a spatial change in the field of the focal plane on one side introduces a linear phase shift in the focal plane on the other side. After

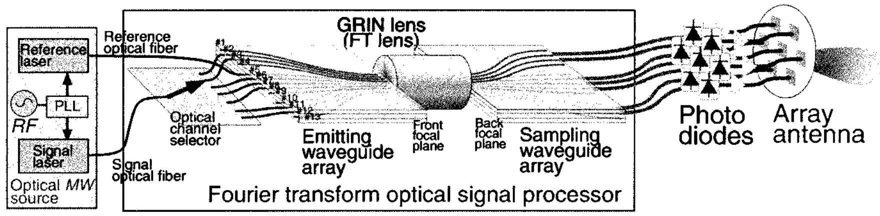

Fig. 5. Experimental setup of the transmitting mode of a 2-D OSP array antenna.

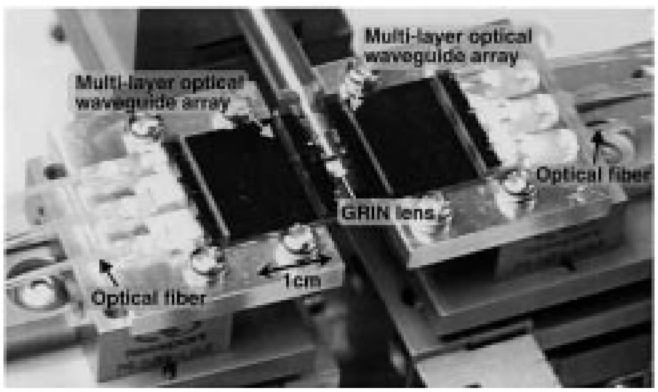

Fig. 6. Assembled 2-D optical signal processor using multilayer optical waveguide arrays.

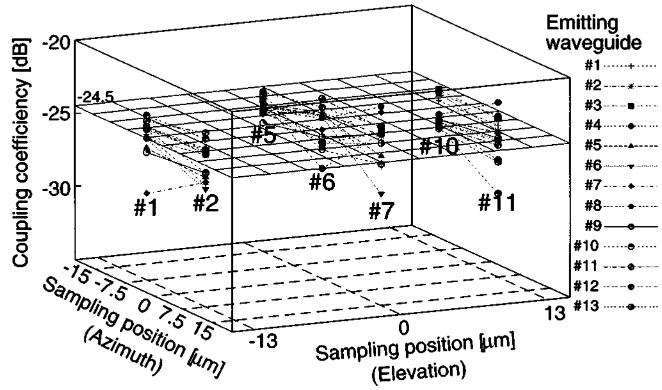

Fig. 7. Measured coupling coefficiencies in 2-D optical signal processor.

transmission through the FT lens, the Gaussian beams keep the Gaussian mode unchanged. The spot size ω_1 in the sampling plane is given by $\omega_{1/2} = \lambda_{\rm opt} f/(\pi\omega_0/2)$, where ω_0 is the spot size of the emitting waveguide. In this manner, when the focal length f is short, ω_1 becomes small, and the light concentrates in the neighborhood of the optical axis. The ideal value of f depends on the element number of the antenna, i.e., the number of sampling waveguides. Here, we assume that seven elements of the array antenna are arranged in a regular triangular lattice, as shown in Fig. 5. The overall diameter of the seven elements of the sampling waveguide becomes $\phi = 38.2$ μm. Accordingly, it is desirable that f be longer than 0.19 mm in order for the light beams to cover the sampling waveguide.

Furthermore, we use a 0.25-pitch Gradient Index (GRIN) micro lens as the FT lens. Its f is 1.34 mm, diameter ϕ is 1 mm, length is 3.2 mm, and numerical aperture (NA) is 0.37. The spot size at the sampling focal plane ω_1 then becomes 280 μm (diameter) in the Gaussian profile. Notably, the 0.25-pitch GRIN lens collimates the point source. Therefore, each front and back focal plane is located on each face of the lens, making rigorous alignment unnecessary.

Fig. 6 shows a photograph of the assembled 2-D OSP using multilayer optical waveguide arrays and GRIN lens. As shown in Fig. 6, the 2-D OSP has been miniaturized.

The optical coupling efficiency between an incident Gaussian beam, with a spot size of ω_1, and a sampling waveguide, with a spot size of ω_2 ($\omega_2 = 8$ μm), is calculated to be [16]

$$\eta = \frac{4}{\left(\dfrac{\omega_1}{\omega_2} + \dfrac{\omega_2}{\omega_1}\right)^2} \exp\left(-\frac{2\left(x^2+y^2\right)}{\omega_1^2+\omega_2^2} - \frac{2\pi^2\theta^2\omega_1^2\omega_2^2}{\lambda^2\left(\omega_1^2+\omega_2^2\right)}\right) \tag{2}$$

where x and y give the distance from the optical axis to the sampling waveguide, and θ is the incident angle. In this experiment, $f = 1.34$ mm, $\omega_2 = 8.2$ μm, and $\omega_1 = 280$ μm. The coupling coefficiency η becomes -24.5 dB.

Fig. 7 shows measurement results of coupling coefficiency η between each waveguide of the emitting array and each waveguide of the sampling array. Each number with "#" is a sampling waveguide number, and each mark corresponds to an optical input port of the emitting array. The measurement values are calibrated by the values of the insertion losses of both the emitting and sampling waveguide arrays, as shown in Fig. 4. From Fig. 7, the average coupling coefficiency η is -25 dB, with a standard deviation of 1.4 dB, and this result agrees with the calculated result.

B. Phase Distribution of Generated Microwave Signal

Fig. 8 shows measured relative phase distributions of microwave signals using a network analyzer, in reference to the phase from port #7 of the sampling waveguide. The reference light was input into port #5 of the emitting waveguide, and the signal lasers were input into the other ports. The output signal from the sampling waveguide was photoelectrically converted to microwave by a PD. The generated microwave signal frequency, i.e., the frequency difference of the reference and signal lasers, was in the X-band.

In Fig. 8, each plane represents the calculated value of each port. As shown in Fig. 8, the measurement results well agree with the calculation results. We could confirm a shift of the 2-D phase distribution of the microwave signals by a change in the port of the emitting waveguide.

Here, the experiment was carried out in the X-band. However, because the OSP–BFN is independent of the microwave

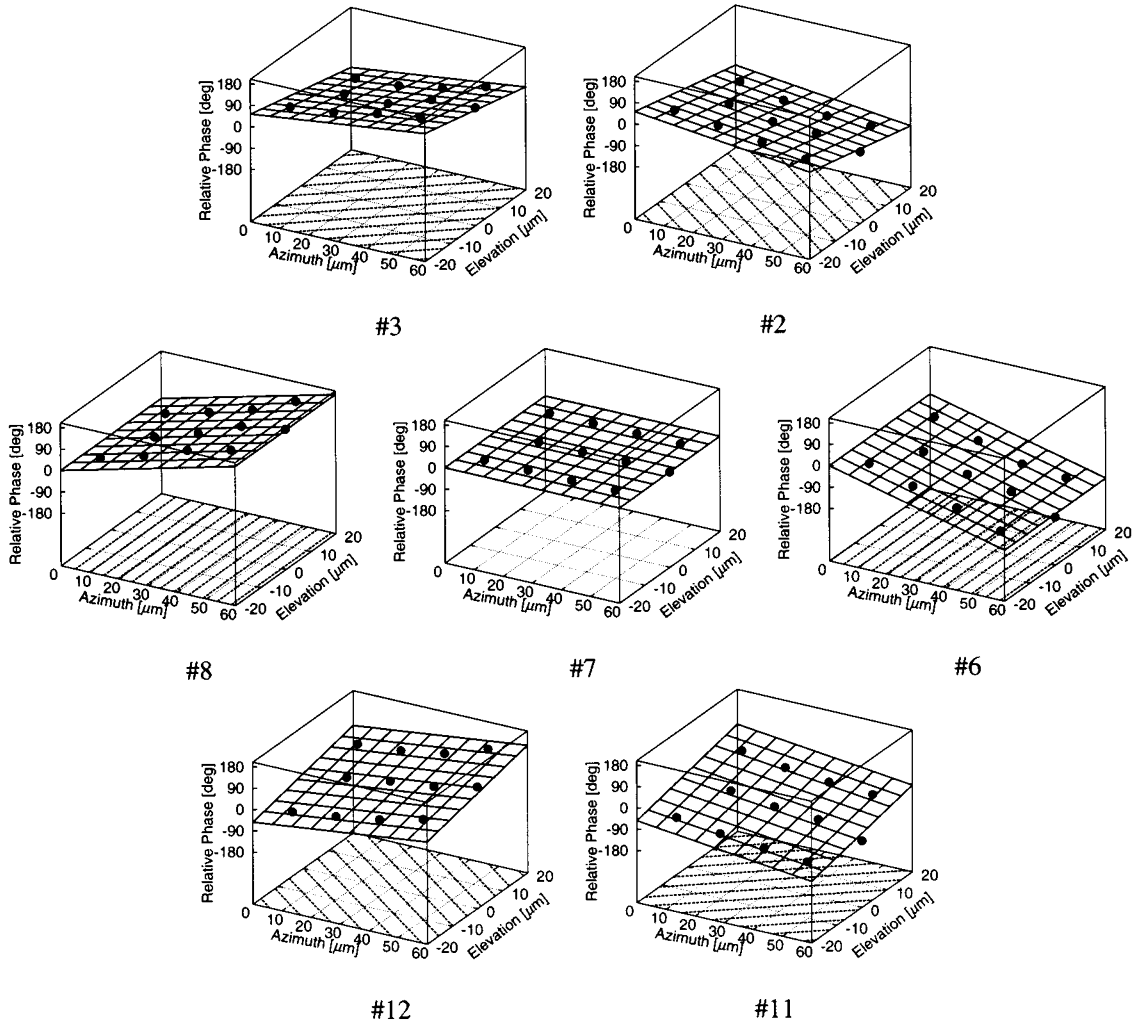

Fig. 8. Measured relative 2-D phase distributions of detected microwave (X-band) signals. ●: measured, plane: calculated.

frequency, if we had carried out experiments in different frequency bands, such as the millimeter-wave frequency band, the results would certainly have been the same [10].

C. Antenna Radiation Patterns

We measured array antenna radiation patterns in an anechoic chamber, as shown in Fig. 5. The array antenna was an X-band seven-element 2-D array antenna with a 0.75-wavelength spacing (horizontal direction) and $1.5\sqrt{3}/2$–wavelength spacing (vertical direction). It had a regular triangular lattice array, and each element was a rectangular patch antenna. Fig. 9 shows measured far-field radiation patterns when the connection port of the signal laser is changed using an optical channel selector. In Fig. 9, "×" represents a calculated main beam direction from (1). These results show that the expected beam control could be achieved. The gain of the main beam should become the same as that in the measured beam direction, but in the measurement results, gain degradation (maximum 3.8 dB) was observed. This degradation was caused by the nonuniformity of the optical coupling coefficient, as shown in Fig. 7.

In this experiment, since the core pitch of the waveguide array was made narrow, the beam-scanning angle was small. How-

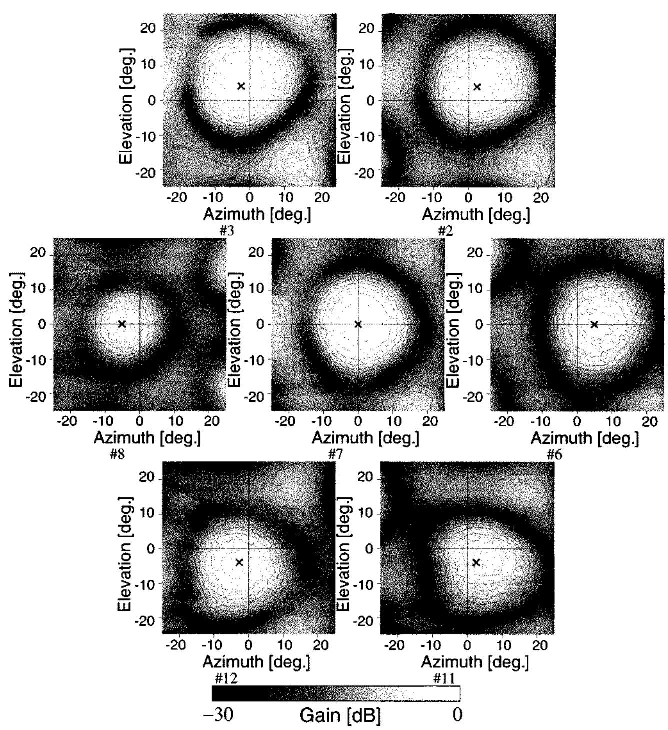

Fig. 9. Measurement results of 2-D antenna radiation patterns.

ever, the beam-scanning angle can be easily enlarged if we make the waveguide pitch wider and each layer thicker.

V. Conclusions

In this paper, we have fabricated the polymeric multilayer optical waveguide arrays and developed a 2-D OSP–BFN using these multilayer optical waveguide arrays. The fabricated optical waveguide arrays are composed of three layers and 13 waveguides (4+5+4). Each waveguide array forms a regular triangular lattice arrangement. The waveguide array has a 15-μm horizontal core pitch and a $15\sqrt{3}/2$-μm vertical core pitch. The pattern and thickness of each waveguide array were fabricated in a very high precision. The insertion losses of each waveguide were approximately 2.2 dB, and the crosstalk in the waveguide array was found to be small (mostly below -30 dB). The 2-D OSP–BFN was constructed using these multilayer optical waveguide arrays and a GRIN micro lens with a focal length of 1.34 mm. In experiments, we could confirm a 2-D phase control characteristic. The output signal from the 2-D OSP–BFN was fed to each antenna element of the 2-D array antenna, and 2-D beam control was demonstrated.

Without changing the 2-D OSP–BFN's organization, 2-D multibeams can be achieved easily by adding lasers to the optical microwave source [8], [17]. Moreover, a 2-D reception BFN can be easily achieved by using the output signal from the OSP as a local signal [9], [18].

Future work includes increasing the number of waveguides of each layer and the layers of the multilayer optical waveguide array.

Acknowledgment

The authors would like to thank Dr. I. Chiba, Mitsubishi Electric Corporation, Kanagawa, Japan, for his helpful discussions, NTT Advanced Technology Corporation, Ibaraki-ken, Japan, for the waveguide fabrication and measurements, and Dr. B. Komiyama, ATR Adaptive Communications Research Laboratories, Kyoto, Japan, for his continuous encouragement.

References

[1] N. Riza, Ed., *Selected Papers on Photonic Control Systems for Phased Array Antenna*. ser. SPIE Milestone. Bellingham, WA: SPIE Opt. Eng. Press, 1997, vol. MS 136.

[2] A. Kumar, *Antenna Design with Fiber Optics*. Norwood, MA: Artech House, 1996.

[3] Beamforming techniques for active phased array antenna based communication satellites. presented at 1999 IEEE MTT-S Int. Microwave Symp. Workshop

[4] P. J. Matthews, "Practical photonic beamforming," in *Int. Microwave Photon. Topical Meeting*, 1999, pp. 271–274,.

[5] G. A. Koepf, "Optical processor for phased-array antenna beamformation," in *Proc. SPIE Opt. Technol. Microwave Applicat.*, vol. 477, 1984, pp. 75–81.

[6] L. P. Anderson, F. Boldissar, and D. C. D. Cheng, "Antenna beamforming using optical processing," *Proc. SPIE*, vol. 886, pp. 228–232, 1988.

[7] K. Konishi, W. Chuju, M. Fujise, and K. Yamada, "Beam scanning characteristics of an optically controlled array antenna fed by a fiber optic array," *Trans. IEICE*, vol. J78-B-II, no. 3, pp. 150–159, 1995.

[8] Y. Ji, K. Inagaki, R. Miura, and Y. Karasawa, "Optical processing for multibeam microwave array antennas," *Electron. Lett.*, vol. 23, no. 9, pp. 822–824, 1996.

[9] Y. Ji, K. Inagaki, O. Shibata, and Y. Karasawa, "Receive mode of optical signal processing multibeam array antennas," *IEEE Microwave Guided Wave Lett.*, vol. 8, pp. 251–253, July 1998.

[10] K. Yamada, I. Chiba, and Y. Karasawa, "Frequency characteristics of a beamforming network of an optically controlled array antenna and its radiation pattern measurement," *Trans. IEICE*, vol. E79-C, pp. 68–73, Jan. 1996.

[11] I. Ogawa, K. Horikawa, T. Kitoh, and H. Ogawa, "Novel multibeam forming network miniaturized by optical slab waveguide," in *Proc. Int. Antenna Propagat. Symp.*, 1996, pp. 121–124.

[12] T. Akiyama, K. Inagaki, Y. Mizuguchi, and T. Ohira, "Multibeam optical signal processing array antenna using optical waveguide arrays and lens," *Trans. IEICE*, vol. E84-B, pp. 2413–2420, Sept. 2001.

[13] I. Ogawa, K. Horikawa, T. Kitoh, A. Himeno, and H. Ogawa, "Two-dimensional multiple beam forming using slab-waveguide-implemented photonic beam forming network," in *Int. Microwave Photon. Topical Meeting*, 1996, pp. 197–200.

[14] M. Hikita, S. Tamaru, K. Enbutsu, N. Ooba, R. Yoshimura, M. Usui, T. Yoshida, and S. Imamura, "Polymeric optical waveguide films for short-distance optical interconnects," *IEEE J. Select. Topics Quantum Electron.*, vol. 5, pp. 1237–1242, May 1999.

[15] M. Usui, M. Hikita, R. Yoshimura, S. Tamaru, S. Imamura, K. Katsura, and Y. Ando, "Basic evaluation of polymeric optical waveguide films applied to optical interconnections," *IEICE Trans. Electron.*, vol. E81-C, no. 7, pp. 1027–1033, 1998.

[16] M. Saruwatari and K. Nawata, "Semiconductor laser to single-mode fiber coupler," *Appl. Opt.*, vol. 18, no. 11, pp. 1847–1856, 1979.

[17] T. Akiyama, K. Inagaki, and Y. Mizuguchi, "Beam-steering and multibeam formation of Ku-band phased array antenna using optical signal processing beam-forming network," in *Int. Microwave Photon. Topical Meeting*, 1999, pp. 173–176.

[18] T. Akiyama, K. Inagaki, Y. Mizuguchi, and T. Ohira, "Beam-steering of receiving array antenna using local signal beamformer by optical signal processing," in *Int. Microwave Photon. Topical Meeting*, 2000, pp. 89–92.

Tomohiro Akiyama (M'00) was born in Tokyo, Japan, in 1965. He received the B.E. and M.E. degrees in electrical and computer engineering from Yokohama National University, Yokohama, Japan, in 1989, and 1991, respectively.

In 1991, he joined the Mitsubishi Electric Corporation, Kamakura, Japan, where he was engaged in research on electrooptic (EO) imaging systems and remote sensing. From 1997 to 2000, he was with ATR Adaptive Communications Research Laboratories, Kyoto, Japan, where he was engaged in research on microwave photonics for wireless communication. In 2001, he returned to the Mitsubishi Electric Corporation, where he is currently a Senior Researcher in the Information Technology Research and Development Center.

Mr. Akiyama is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan and the IEEE Lasers and Electro-Optics Society (IEEE LEOS).

Keizo Inagaki (M'92) was born in Osaka, Japan, in 1961. He received the B.S. and M.S. degrees in electrical engineering from Kyoto University, Kyoto, Japan, in 1985 and 1987, respectively.

In 1987, he joined ATR Optical and Radio Communications Research Laboratories, where he was engaged in the research and development of free-space laser communication system. Since 1996, he has been with ATR Adaptive Communications Research Laboratories, Kyoto, Japan, where he has been involved with the research of OSP antennas and optical phased-array antennas.

Mr. Inagaki is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan.

Takashi Ohira (S'79–M'80–SM'99) was born in Osaka, Japan, in 1955. He received the B.E. and D.E. degrees in communication engineering from Osaka University, Osaka, Japan, in 1978 and 1983, respectively.

In 1983, he joined NTT Electrical Communication Laboratories, Yokosuka, Japan, where he was engaged in research on monolithic integration of microwave semiconductor devices and circuits. In 1987, he developed GaAs monolithic-microwave integrated-circuit (MMIC) transponder modules and microwave BFNs aboard Japanese domestic multibeam communication satellites, Engineering Test Satellite VI (ETS-VI), and ETS-VIII, at NTT Wireless Systems Laboratories, Yokosuka, Japan. Since 1999, he has been engaged in research on microwave analog adaptive antennas at ATR Adaptive Communications Research Laboratories, Kyoto, Japan. He co-authored *MMIC* (Tokyo, Japan: IEICE Press, 1997).

Dr. Ohira is the National Astronautical Space Development Agency (NASDA) ETS-VIII Project consulting engineer, and the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) Japan chapter vice-chairperson. He was the recipient of the 1986 Shinohara Prize and the 1998 Asia–Pacific Microwave Conference (APMC) Prize.

Makoto Hikita was born in Tokyo, Japan, in 1950. He received the B.E. and M.E. degrees in instrumentation engineering from Keio University, Keio, Japan, in 1973 and 1975, respectively, and the Ph.D. degree in physics from Osaka University, Osaka, Japan, in 1990.

In 1975, he joined NTT Musashino Laboratories, Tokyo, Japan, where he was engaged in research on superconducting telecommunication cables. In 1980, he moved to NTT Ibaraki Laboratories, Ibaraki, Japan, where he was engaged in research on superconducting materials, Josephson devices, Anderson localization, and superconducting physics. In 1992, he was engaged in the development of electrooptic and passive polymer optical component devices. In 2000, he joined the NTT Advanced Technology Corporation (NTT-AT), Ibaraki-ken, Japan, where he is currently a Senior Engineer.

Dr. Hikita is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan, the Physical Society of Japan, the Society of Polymer Science of Japan, the Japan Society of Applied Physics, the Japan Institute of Electronics Packaging.