PROCEEDINGS OF ISAP '96, CHIBA, JAPAN

Novel Multibeam Forming Network Miniaturized by Optical Slab Waveguide

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Abstract

This paper proposes a novel multibeam forming network (BFN) miniaturized using an optical slab waveguide. The slab waveguide enables photonic BFNs to drastically reduce the size and loss by making the best of planar lightwave circuits. In this BFN, a microwave signal is processed in the optical domain using the heterodyne technique. A slab waveguide is fabricated using SiO_2/Si waveguide and the basic performance is tested at 2.5-GHz microwave frequency. The experimental results show that the BFN has a low loss feature and capability of multibeam forming.

I. Introduction

Optically controlled phased array antennas have been investigated to achieve large capacity and flexible beam forming functions. Although several types of photonic multibeam forming networks (BFNs) have already been proposed and demonstrated [1]-[6], there has not yet been sufficient discussion of multibeam forming networks. Due to the fact that typical BFNs allocate phase shifters and attenuators for each path to an array element, the photonic circuit becomes too complex to construct a multibeam forming network. In addition, combining and interconnecting losses, which increase according to the number of beam and array elements, are unavoidable in typical BFNs.

One solution to this problem is combining an optical Fourier transform and the heterodyne technique [5]-[6]. Although spatial optical processing using a Fourier transform lens and array fibers is an attractive approach, further development is required for achieving precise and stable alignment of fibers and the other components.

In this paper, we propose a novel beam forming network that uses an optical slab waveguide and the heterodyne method. Since the slab waveguide used here works both as a star coupler and an optical Fourier transformer, the BFN configuration is simplified and the combining and interconnecting losses are eliminated. Moreover, because the slab waveguide is fabricated using a planar circuit, miniaturization and precise fabrication of the BFN can be easily achieved. In the following sections, we describe the BFN configuration, and report on the experimental results.

II. Principle and BFN Configuration

Figure 1 shows the schematic layout of the slab waveguide [7]. The waveguide consists of a slab region and M x N input/output waveguides on both sides of the slab region. The interface between the slab and input/output waveguides is located on the arc with curvature radius R. The input/output waveguides are placed at spacing $d1$ and $d2$ respectively, and each waveguide end region faces the center waveguide on the other interface. In this report, the output waveguide aperture is widened to reduce slab-waveguide coupling loss.

The principle of operation is explained below. The input light radiates to the slab waveguide, and then excites the output waveguides. Assuming the mode field pattern of the input waveguide as Gaussian, the optical amplitude distribution, $Aopt$, of the output waveguides is approximately Gaussian shaped for a comparably large R, described as

$$Aopt = \alpha \cdot \exp\left[\left(\frac{x}{\omega_R}\right)^2\right] \qquad (1)$$

here, α is the amplitude of the center waveguide. ω_R corresponds to the spot size at the interface. On the other hand, excited optical phase Φopt is determined by propagation length L and wavelength λopt.

$$\Phi opt = \frac{2 \cdot \pi \cdot n_{eff} \cdot L}{\lambda opt} \tag{2}$$

here, n_{eff} is the effective refractive index of the slab region.

Microwaves are generated and controlled using the slab waveguide together with the heterodyne technique. The desired microwave is regenerated as the beat of two lightwaves and controlled by selecting two proper input waveguides for the two lightwaves. The microwave amplitude, *Amw*, and phase Φmw correspond to the amplitude product and the phase difference of two the lightwaves, expressed as

$$Amw = Aopt_1 \cdot Aopt_2 \tag{3}$$

$$\Phi mw = \Phi opt_1 - \Phi opt_2 \tag{4}$$

As a result, the amplitude distribution of the obtained microwave is also Gaussian, while the phase distribution has a linear inclination in the case where slab arc radius *R* is sufficiently larger than the width of the interface region.

Using this slab waveguide, a multiple beam forming network is easily constructed as shown in Figure 2. In this figure, one reference and (M-1) signal lightwaves are coupled to respective input waveguides so that M microwaves with different phase distributions are obtained at O/E converters. The optical frequency shifters [3] may be a suitable way for preparing these lightwave signals. By using this configuration, miniaturizing the BFN and eliminating the combining and interconnecting losses are achieved simultaneously.

Designed parameters of the fabricated waveguide are shown in Table 1. A 32 x 32 SiO_2/Si slab waveguide was fabricated using silica-based planar lightwave circuit technology [7]-[8]. A cross-sectional view of the waveguide is given in Figure 3. The waveguide core was 7 μm x 7 μm and the refractive index difference between core and cladding was 0.75%. Using the parameters in Table 1, 8 beams are formed using 9 central input ports in radiating angles of -53 to +53 degrees and within the amplitude variation of 1.7 dB among the 8 beams. This variation occurs because of the Gaussian power distribution, i.e., the insertion loss for the peripheral input waveguide becomes larger than the central one.

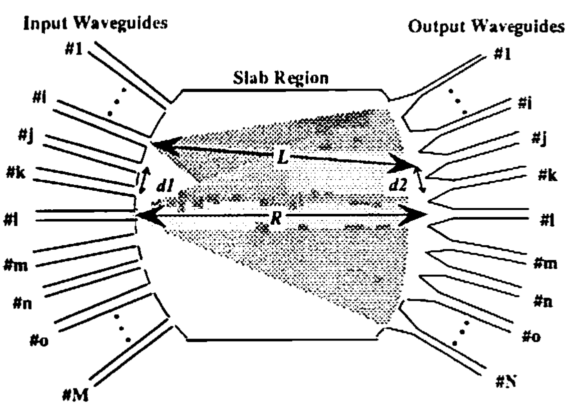

Figure 1. Schematic Layout of Slab Waveguide

Table 1. Designed Value of Fabricated Slab Waveguide

Symbol	Designed Value
R	7000 μm
$d1$	25 μm
$d2$	25 μm
M	32
N	32

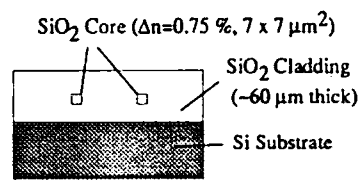

Figure 3. Cross-sectional View of Silica Waveguide

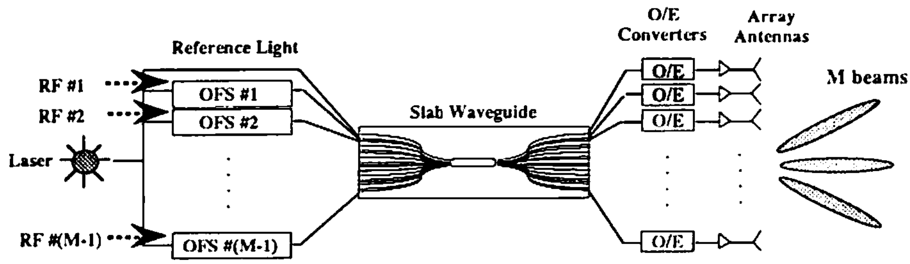

Figure 2. BFN Configuration

III. Experimental Results

(1) Experimental Setup

The experimental setup is shown in Figure 4. The reference and signal lights were prepared by using two 1.32 μm phase-locked Nd-YAG lasers. The frequency deviation of two lightwaves was set to 2.5 GHz. The amplitude and phase of the 2.5-GHz microwave signal from two output ports were observed and compared by a network analyzer. Through the experiment, fibers and waveguides were coupled using micro positioners. The reference light was coupled to input waveguide #16 to all beams, while the signal light was coupled to an appropriate input waveguide in order to obtain the desired beam.

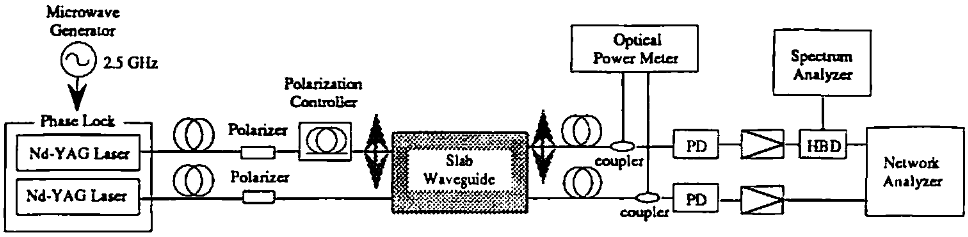

Figure 4. Experimental Setup

(2) Experimental Results

Optical loss characteristics for the 9 central input ports, #12 to #20, are shown in Table 2. The total insertion loss for input port #16 was 3.5 dB including fiber coupling loss and propagation loss. Assuming the fiber coupling loss of 0.5 dB/point and the propagation loss of 0.7 dB/7 cm, the 32 dividing excess loss is estimated to be 1.8 dB. As described in Section II, an additional loss of 1.3 dB was observed between the central and peripheral input ports because of the Gaussian power distribution.

Table 2. Optical Loss Characteristics

Type of Loss	Estimated Value
Fiber Coupling Loss (Conventional Value)	0.5 dB/point x 2
Propagation Loss (Conventional Value)	0.1 dB/cm x 7 cm
32 dividing excess loss (including slab-waveguide coupling loss)	1.8 - 3.1 dB
Total Insertion Loss	3.5 - 4.8 dB

Figure 5 shows the relative amplitude distribution of the observed 2.5-GHz microwave signal. Thin lines correspond to the measured distributions for the 8 input ports, while the thick line represents the designed one for the center beam. The measured distributions had the Gaussian shape and agree with the designed ones. Figure 6 shows the relative phase distribution. Solid lines and marks represent the designed and measured values, respectively.

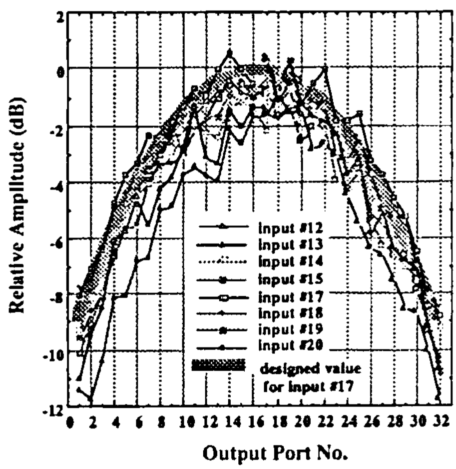

Figure 5. Amplitude Distribution

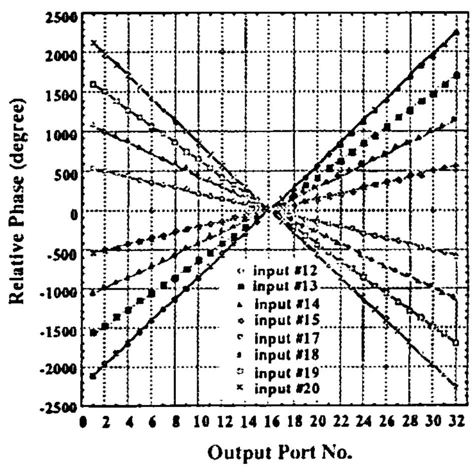

Figure 6. Phase Distribution

Calculated array factors for half wavelength spacing linear array antennas are shown in Figure 7. Solid lines represent the calculated values using the measured amplitude and phase, and dotted lines represent the designed values. The difference between the main-lobe level for the designed array factors and that for the measured factors was less than 1.1 dB. Maximum measured side-lobe degradation was 3.1 dB in comparison with the designed one. These results indicate that the slab waveguide appropriately controls the microwave amplitude and phase distribution.

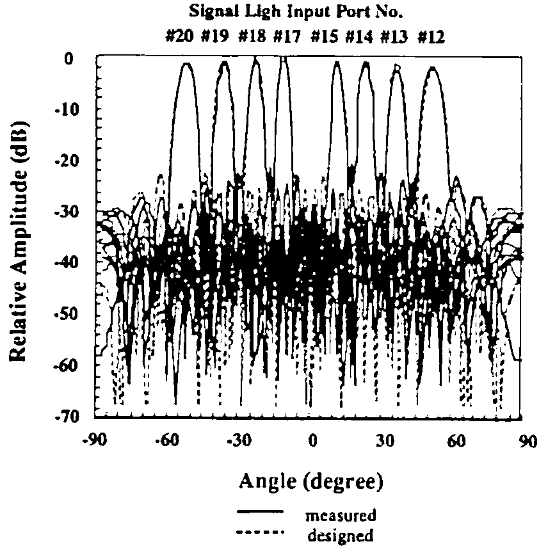

Figure 7. Comparison of Array Factors

IV. Conclusion

A slab-waveguide-implemented photonic beam forming network was proposed. The slab waveguide makes it possible to construct the multibeam forming network simply and to eliminate the combining and interconnecting losses. Moreover, because the slab waveguide is fabricated through the planar device process, miniaturization, and precise fabrication of the BFN are easily achieved.

A 32 x 32 slab waveguide was fabricated using a SiO_2/Si waveguide, and the basic performance was tested in both optical and microwave domains. The measured optical insertion loss ranged from 3.5 to 4.8 dB including the fiber-waveguide coupling loss and the propagation loss. This low loss feature is a great advantage for the present BFN. In the microwave domain, the 8 beam formation using 32 array elements was examined at a microwave frequency of 2.5 GHz. The obtained array factors, which were calculated using the measured microwave amplitude and phase, agree well with the designed ones. These results all show the applicability to the BFN.

Acknowledgment

The authors would like to thank Dr. K. Kohiyama, Dr. S. Samejima, Dr. M. Kawachi and Dr. K. Okamoto for their continuous support and encouragement.

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