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A Novel Configuration of an Optical Signal Processor for Multibeam Array Antennas

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1. Introduction

In recent years significant progress has been made worldwide on the application of optical technologies to microwave phased array antennas. A number of approaches have been proposed for beam-forming, beam-scanning, RF signal distribution and antenna remote control. The advantages of using optics in array antennas are extremely wide bandwidth, reduction in size and weight and immunity from electromagnetic interference and crosstalk.

By applying spatial optical processing techniques, an optical-fed multibeam array antenna has been developed [1], which could be used as a satellite-on-board antenna or a mobile communications base-station. In the conventional microwave Beam Forming Network (BFN), the more the beams are produced, the more complicated matrix circuit, greater number of interconnections and larger BFN are required. In the optical BFN, an optical lens replaces the matrix circuit to implement beam division, interconnection and combination spatially. When the multibeam number increases, the only requirement is to add lasers equivalent to the microwave beams, and there is no change in the BFN part [1], [2]. However, there are two problems when setting up the antenna system. One is the laborious alignment to produce the same size and collinear optical beams spatially. The other is the power loss of the beam transmission in free space. To solve these two difficulties, we propose a new design using optical heterodyne processing technique in this paper. The feature of this design is that the emitting optical fibers connecting both the master lasers and the reference laser are arranged in the same axis in parallel.

This paper will concentrate on the optical heterodyne processing principle and optical processor design and analysis. The initial experimental results will also be given.

2. System Design and Analysis

To generate and control a microwave signal with a particular phase shift, the optical heterodyne is a very effect procedure [3]. This process needs two frequency offset optical beams which could be from the same laser source or from two phase locked laser sources [4]. When these two laser beams from different directions are incident on an optical fiber array, a moving sinusoidal interference pattern can be generated and sampled by each of fiber, and the moving rate equals the offset frequency. The RF signal with a phase shift determined by the incident angles can be detected by photodetectors connected to the fiber array.

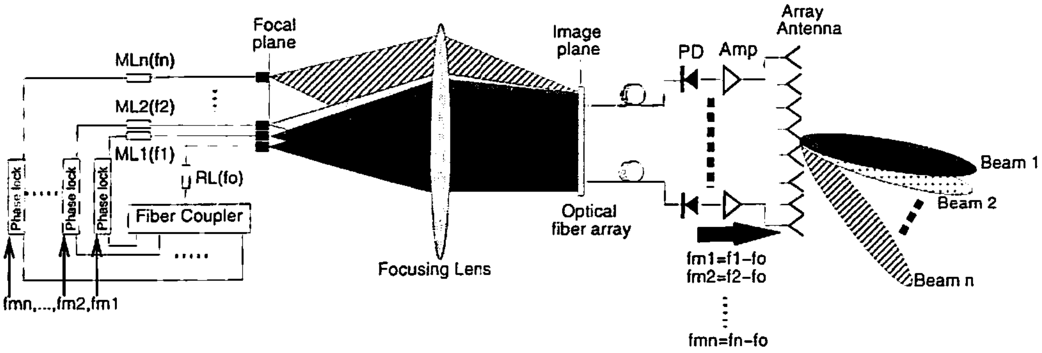

Fig. 1 Proposed optical signal processor for multibeam array antenna

We propose a new type of optical heterodyne processor for multibeam array antennas. Fig. 1 illustrates the system diagram in which only one focusing lens is employed to focus the beams from both master lasers (ML) and a reference laser (RL), and the beam combiner used in the conventional design is omitted. This design will greatly reduce the optical alignment difficulties, the free-space light transmission loss, and the size of the optical processing feed part.

Fig. 2 shows how three Gaussian beams from optical single-mode fibers (the one on the axis is the reference beam and the others are master beams) transmit to a focusing lens and mix together in the image plane. The dotted lines inside the solid Gaussian distribution envelope in the image plane are the moving sinusoidal interference patterns. Since an ideal lens only changes the Gaussian beam size but not the beam mode, after transmission through the lens, the beams will keep the Gaussian mode unchanged.

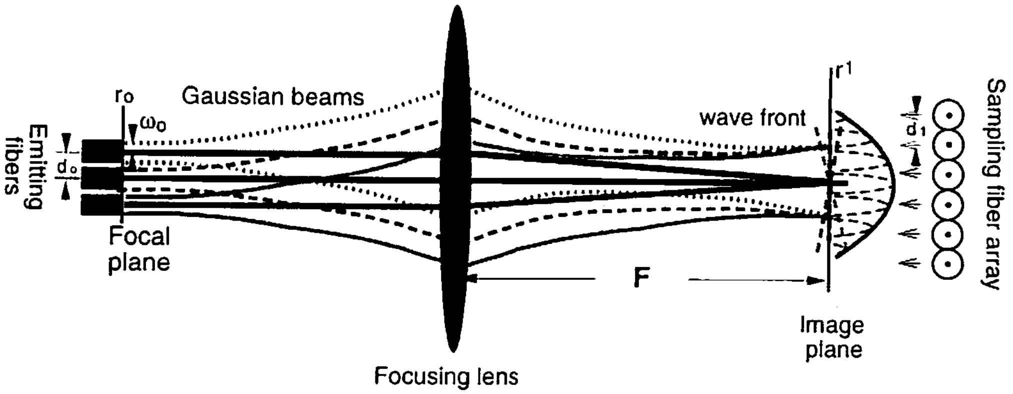

Fig. 2 Parallel optical processing of Gaussian beams by using focusing lens

From the well known Shift Theorem of a focusing lens, that is, a spatial change of the field in the focal plane of one side introduces a linear phase shift in the focal plane of another side, the optical interference excitation field distributions in the sampling plane (x1,y1,z1) by mixing an arbitrary master beam and a reference beam can be expressed as

$$E_z(r_1) = A_m A_r e^{-r_1^2/\omega_1^2} e^{j2\pi r_1 \cdot r_0/\lambda F}. \tag{1}$$

In Eq.(1), Am and Ar are amplitudes of the master and reference beams respectively; the beam radius is given by $\omega_1 = \lambda F/\pi\omega_0$, where ωo is the beam waist, F is the focal length of the lens and λ is the wave length of light: ro denotes the location of the fibers emitting the master laser beams. The real part in Eq.(1) refers to the instantaneous interference patterns which move with time by the rate of frequency difference between the two lasers.

We note that to detect the RF signals which are equal to the moving interference pattern rate, at least one sampling fiber should be placed between each of the adjacent nulls of interference pattern, and the distance between the nulls increases as the fibers of the master lasers become farther from the optical axis. Therefore, the maximum number of the array antenna multiple beams in one dimension which equals the number of emitting fibers can be decided by

$$M = \frac{\lambda F}{d_0 d_1}, \tag{2}$$

where do is the distance between two adjacent emitting fiber centers and d1 is the distance between two adjacent sampling fiber centers as shown in Fig. 2.

Since the instantaneous light interference pattern sampled by the fibers will be time-averaged as a Gaussian distribution by photodetectors, the far-field radiation pattern of the microwave array antenna is given by

$$E_R(\theta) = \sum_{n=-N}^{N} A_m A_r e^{-n^2 d_1^2 / \omega_1^2} \exp[jnk(d_m \cos\theta - \frac{d_1 \hat{r}_1 \bullet \bar{r}_o}{F}), \tag{3}$$

where the total element number of both the optical sampling fiber array and the microwave antenna array is decided by $2N + 1 = \frac{2\lambda F}{\pi d_o \omega_o}$, and dm is the interelement spacing of the antenna array.

3. Numerical and Experimental Results

The instantaneous light interference patterns between the master beams emitted from the fibers with a GRIN lens 125 μm from the optical axis. and the reference beams from the fiber on optical axis are shown in Fig. 3. The GRIN lens is employed to produce overlapping multiple beams and reduce the power loss as discussed in Ref. (1).

Numerical simulated multibeam radiation patterns of three overlapping multiple beams are shown in Fig. 4. Through numerical calculations, some trends on antenna radiation patterns have been found: (a) as F increases, the main lobe narrows and the side lobe level increases; (b) as N increases, the main lobe narrows and the side lobe level decreases: (c) as d1 increases, the main lobe widens and the side lobe level decreases.

Variations of the maximum number of multiple beams and the number of sampling fibers or antenna elements versus the distance between sampling fibers and the focal length of the focusing lens are shown in Figs. 5 and 6, respectively. These graphs indicate that the number of multibeams and the antenna size can be increased greatly by integrating a sampling fiber array to an optical waveguide array.

A two-beam optical processor has been set up. Three single-mode fibers, which are connected to three LD pumped Nd:YAG tunable lasers in the 1.319 μm region with output power of roughly 50 mw, were fixed as close as possible in parallel in one focal plane of a lens. Two master lasers were phase-locked to a reference laser with frequency offsets of 900 MHz and 1 GHz separately. The three laser beams transmit through a focusing lens, mix together spatially, and then are sampled by a lens-ended optical fiber. The spectra of multiple relatively high level RF signals are shown in Fig. 7 as detected by a photodetector.

4. Conclusion

In this paper, a simple optical signal processor for multibeam microwave array antennas has been proposed, based on optical heterodyne processing and quasi-optics principles, and a system design and analysis method has been given. Numerically calculated instantaneous light interference patterns and overlapping multibeam radiation patterns have been presented. The numerical results of system parameter simulations have shown that an extremely-wideband microwave antenna with a large beam number and array element number can be realized by using this optical processor. As an initial stage, a two-beam experimental optical processor for producing RF signals (900 MHz and 1 GHz) has been demonstrated.

By employing the proposed optical processor, the performance of a multibeam array antenna that can produce more beams and operate at higher frequencies will be presented in the near future.

References:

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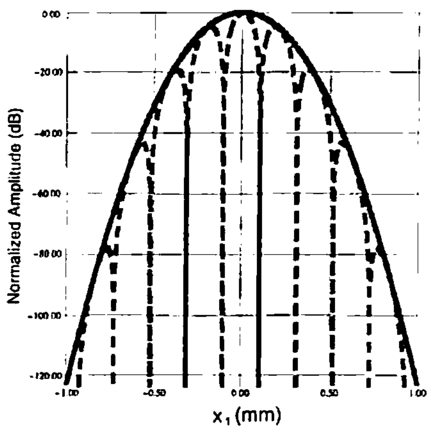

Fig. 3 Light interference pattern (dotted) with Gaussian envelope (solid) in the image plane of focusing lens.

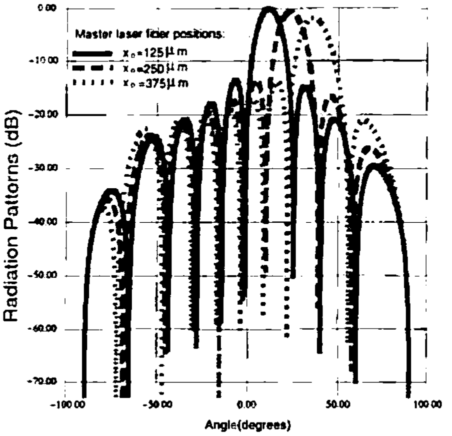

Fig. 4 Calculated microwave array antenna multibeam patterns, where the element number of antenna array N is 9.

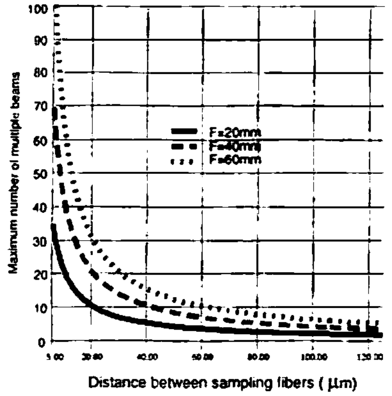

Fig. 5 Variations of maximum number of multiple beams versus the spacing between sampling fibers and the focal length of focusing lens, when λ=1.3 μm, do=125 μm.

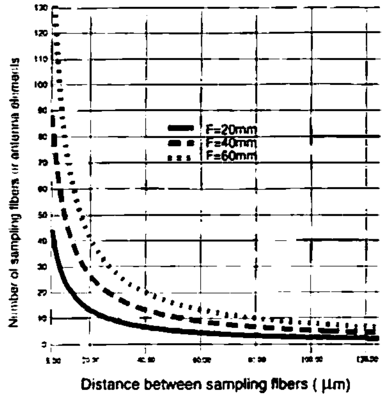

Fig. 6 Variations of the number of sampling fibers or antenna elements versus the spacing between sampling fibers and the focal length of focusing lens, when λ=1.3 μm, ωo=62.5 μm.

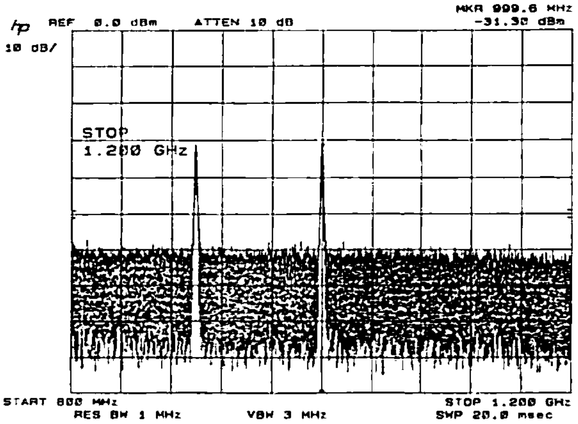

Fig. 7 Detected RF signals at 900 MHz and 1 GHz from the sampling fibers located in the image plane of focusing lens.