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Optical Signal Processing Multibeam Array Antennas for both Transmission and Reception

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Abstract---- Recent studies have investigated the application of optical or photonic technology to microwave array antennas for signal processing and beam formation. However, there have been few practical systems reported, and no report has been made on practical multibeam applications and its receive mode. This technical report summarizes the research works on the optical signal processing array antenna for transmission and reception of multiple beams, which was conducted at ATR Adaptive Communications Research Laboratory from April 1996 to August 1997. The beam forming network (BFN) of this antenna was achieved by using Fourier optics principles and optical heterodyne techniques. In Chapter 1, the structure of the optical processing feed is given along with consideration of overlapping multiple beams generation. The systems parameter design method and evaluation of optical power loss during processing are also described. A proof-of-concept experimental demonstration of the optical processor used for a 2-beam array antenna in the Ku is also shown in Chapter 1. Ultra-wideband, ultra-stable and high-level microwave signals are obtained. Measured amplitude and phase distributions of optical excitation to the array antenna show very good agreement with the calculated results. In Chapter 2, the concept and experimental examination of the receive mode of the optical processing multibeam array antennas are given. In this receive mode, the generated RF signals by optical processor will be shifted as LO signals, and the received RF beams will be discriminated in the downconverted IF frequency domain by a mixer array between optical processor and antenna elements. Chapter 3 gives a summary of this technical report and the problems in the future development.

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Chapter 1

Transmit Mode of the Optical Signal Processing Array Antenna

1.1. INTRODUCTION

Future wireless telecommunications will require compact, light-weight antennas having flexible control of beam forming/steering and a large number of multiple beams. Reflector, lens and phased array are three basic types of candidate antennas. Compared with reflector and lens types, the array antenna has a number of advantages: higher aperture efficiency, no spillover loss, no aperture blockage and better reliability; however, its disadvantages are heavy weight, complexity, and higher loss in the power distribution system. To keep these advantages and overcome these disadvantages, significant worldwide progress has been made in recent years on the application of optical techniques to microwave phased array antennas. By using optical components, the size and weight of array antennas can be greatly reduced, and the microwave field distributions on the antenna aperture can be controlled in the optical domain. A number of approaches have been proposed for beam-forming, beam-scanning, RF signal distribution and remote control of antennas [1-6]. The advantages of using optical techniques in array antennas include extremely wide bandwidth, miniaturization, reduced weight and immunity from electromagnetic interference and crosstalk.

First of all, this Chapter starts from the principle of optical heterodyne and single-beam formation by a Fourier optical processor feeding a microwave array antenna. The optical power loss during signal processing and sampling is also discussed. The basic concept and configuration of the coherent Fourier optical processor for array antenna beam forming and steering were proposed by Koepf [2] in 1984. Although much attention has been given to the true-time fiber delay technique [7], which allows instantaneous bandwidth and squint-free operation, Fourier optical processing is still an attractive approach for beam shaping, multibeam operation and array feeding with a large number of elements [8].

Secondly, by applying this optical processing technique which employs a Fourier transform lens to realize large-number signal processing in parallel, the optically-fed multibeam array antennas that can be used as satellite-on-board antennas or mobile communication base-stations will be described. In the conventional microwave Beam Forming Network (BFN), producing more beams requires more complicated matrix circuit, more interconnections and a larger BFN. For large-number multibeam array antennas, a critical problem is how to reduce the BFN's size and weight. In an optical BFN, an optical lens is used in place of the matrix circuit to implement the beam division, interconnection and combination spatially. When the beam number increases, only lasers equivalent to the number of microwave beams are required, and there is no change in the BFN part. The initial experimental results have demonstrated the effectiveness of this structure [9]. However, there are two problems when we set up the actual antenna system. One is the laborious alignment needed for producing the same-sized and collinear optical beams spatially. The other is the power loss of the beam transmission in free space. To solve these two difficulties, in this paper we will propose a new configuration for the optical processor, where the emitting optical fibers from both the master lasers and the reference laser will be arranged in the same axis in parallel.

Finally, a proof-of-concept experimental demonstration for a 2-beam array antenna in the Ku band will be described in this Chapter. The detected microwave amplitude and phase distributions in the image plane of the optical processor as array antenna excitation will be given with a comparison of the calculated data.

1.2. PRINCIPLE OF OPTICAL SIGNAL PROCESSING FOR ARRAY ANTENNA APPLICATIONS

A. Optical Heterodyne

To generate and control a microwave signal with a particular phase shift, the optical heterodyne is a very effective procedure [10]. This technique requires two frequency offset optical beams that could be from either the same laser source or from two phase locked coherent laser sources. When these two laser beams from different directions are incident on an optical fiber array, a moving sinusoidal interference pattern appears and is sampled by each fiber, and the moving rate is equal to 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.

In optical heterodyne processing, producing stable RF signals effectively requires two incident optical beams having the same polarization, say, for example in the x-direction. If we assume the working frequencies of master and reference lasers are Ω_m and Ω_r, respectively, then we will have the following expressions of electric field in an image plane (r_1)

$$\vec{E}_m = \vec{i}_x A_m e^{j\Omega_m t + jk_o \sin\theta_m r_1} \qquad (1.1a)$$

and $\vec{E}_r = \vec{i}_x A_r e^{j\Omega_r t + jk_o \sin\theta_r r_1}$, (1.1b)

where θ_m and θ_r are the beam incident angles, and k_o is the optical wave number.

When we mix these two beams together, the total field is the superimposing of (1.1a) and (1.1b) as

$$\vec{E}_T = \vec{E}_m + \vec{E}_r = \vec{i}_x (A_m e^{j\Omega_m t + jk_o \sin\theta_m r_1} + A_r e^{j\Omega_r t + jk_o \sin\theta_r r_1}), \qquad (1.2)$$

and the total field intensity is obtained by

$$\begin{aligned} I &= \vec{E}_T \cdot \vec{E}_T^{\,*} \\ &= (A_m e^{j\Omega_m t + jk_o \sin\theta_m r_1} + A_r e^{j\Omega_r t + jk_o \sin\theta_r r_1})(A_m e^{-j\Omega_m t - jk_o \sin\theta_m r_1} + A_r e^{-j\Omega_r t - jk_o \sin\theta_r r_1}), \\ &= A_m{}^2 + A_r{}^2 + 2A_m A_r \cos[\Omega_{RF} t + k_o(\sin\theta_m - \sin\theta_r) r_1] \end{aligned} \tag{1.3}$$

where the frequency difference $\Omega_{RF} = \Omega_m - \Omega_r$ is set as the desired antenna RF frequency.

When these mixed optical signals are input to a photodetector, the output photocurrent is proportional to the intensity $2A_mA_r$, and the beat signal of Ω_{RF} is detected to produce a source of radio frequencies.

B. Single Beam Formation

It is well known that the antenna aperture distribution and far-field radiation pattern are a Fourier transform (FT) pair. An optical lens also offers an FT function. Therefore, instead of the conventional microwave BFN, an FT lens used as an optical processor can realize beam formation as shown in Fig.1.1. By using optical heterodyne techniques, array antenna elements are excited by the RF beat signal of the mixed master and reference laser beams in the image plane of the FT lens. The desired antenna pattern is achieved by the scaled illuminating mask pattern in the object focal plane of the FT lens. This configuration allows that the far-field beam patterns to be obtained simply from the same scaled mask patterns, and the antenna beam scanning and steering can be realized by simply moving the mask aperture in the object plane [4]. Therefore, the multibeam and shaped multi-spot function can be implemented by adding other light sources or by making other shaped apertures in the object focal plane.

Instead of a truncated mask pattern in the object plane, when we use a single-mode fiber ended by a variable length GIF (Graded Index Lens) as the input light source, the amplitudes of the optical beams will have a Gaussian distribution. An ideal lens only changes the beam size but not the beam mode, so after transmission through the lens, the beams will keep the Gaussian mode unchanged. Therefore, the field amplitude in Eq. (1.1) as the optical excitation of the array antenna can be written as

$$A_m(or\ A_r) = A_{mo}(or\ A_{ro})\frac{\omega_o}{\omega_1}e^{-r_1^2/\omega_1^2}, \quad (1.4)$$

where ω_1 is the beam waist in the image plane given by $\frac{\lambda_o F}{\pi\omega_o}$, λ_o is the optical wavelength, F is the focal length of the FT lens and ω_o is the beam waist in the object plane.

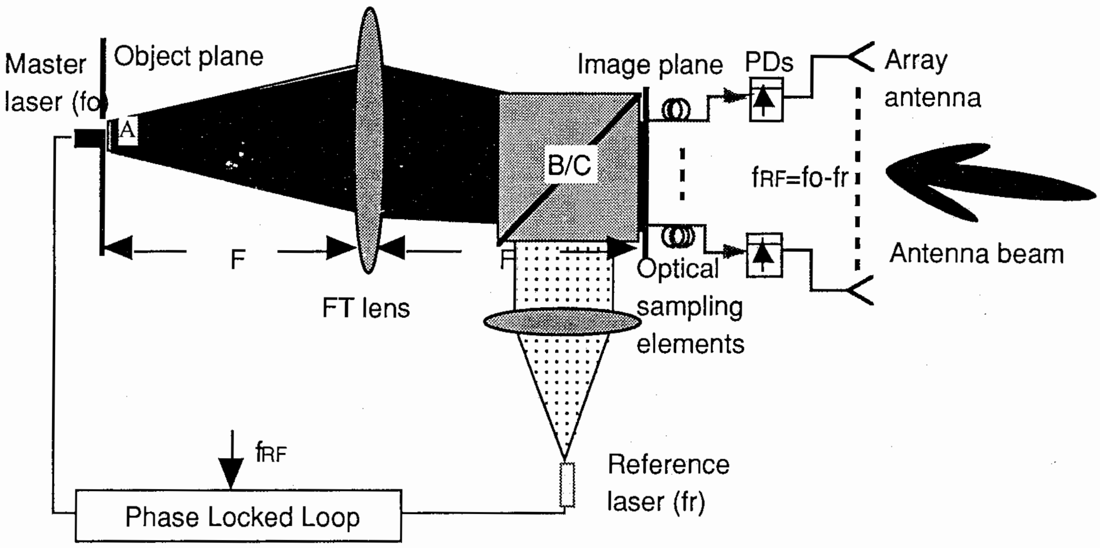

Fig.1.1 Optical signal processing array antenna

From the well known Shift Theorem of a Fourier transform 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 the other side, the field distributions of optical interference excitation in the sampling plane (x_1, y_1, z_1) by mixing an arbitrary master beam located r_o offset the optical axis, and a reference beam located on the optical axis can be expressed by

$$E_o(r_1) = 2A_{mo}A_{ro}\frac{\omega_o}{\omega_1}e^{-r_1^2/\omega_1^2}e^{j2\pi\bar{r}_1\bullet\bar{r}_o/\lambda_o F}. \quad (1.5)$$

The real part in Eq. (1.5) refers to the instantaneous interference patterns that move with time at the rate of frequency difference between the two lasers.

The instantaneous light interference patterns between master laser beam whose center is 125 μm from the optical axis, and a reference beam centered on the optical axis are shown in Fig. 1.2. If the master laser source is located farther from the optical axis, more interference patterns will appear.

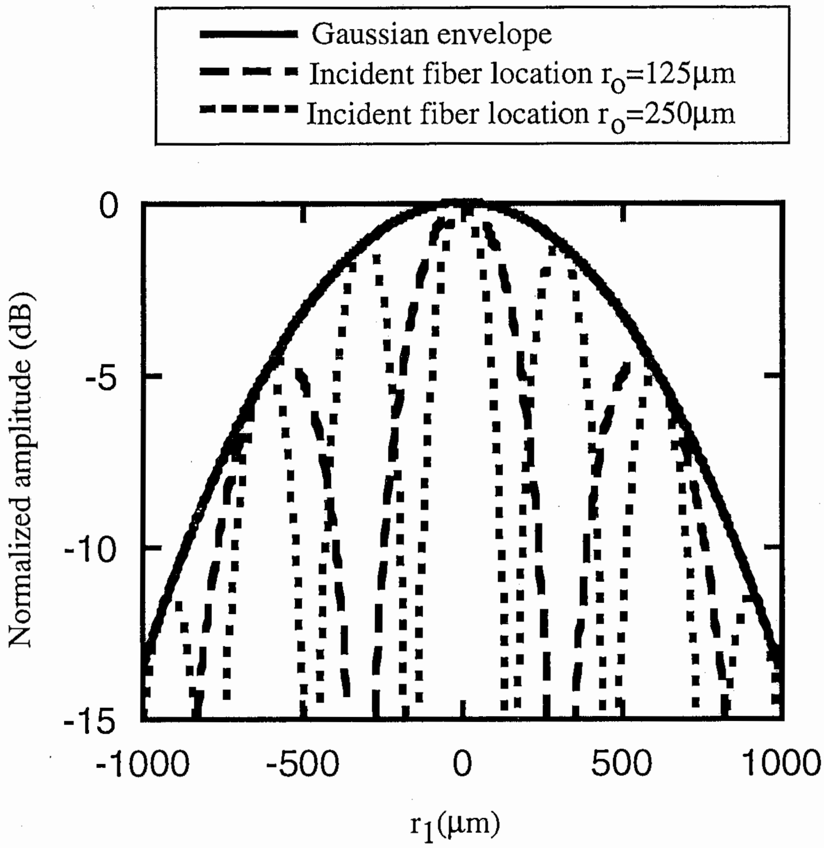

Fig.1.2 Light interference patterns (dotted) with Gaussian envelope (solid) in image plane of focusing lens

Based on Eq. (1.5), since the instantaneous light interference pattern sampled by the optical elements will be time-averaged as a Gaussian distribution by photodetectors, the radiated far-field from array antenna can be written as

$$E(\theta)=\sum_{n=0}^{N}2A_{mo}A_{ro}f_n(\theta)\frac{\omega_o}{\omega_1}e^{-n^2d_1^2/\omega_1^2}\exp[j(nkd_{RF}\sin\theta-2\pi nd_1r_o/\lambda_oF)\quad,\tag{1.6}$$

where $f_n(\theta)$ is the n-th element radiation pattern function, k is the microwave number, and d_1 and d_{RF} are the intervals between the optical sampling elements and the RF array elements.

When a truncated circular light source with a radius of A and r_o offset from the optical axis is used, the optical field distribution in the image plane of the FT lens is produced by a Fourier transform of the beam distribution in the object plane of the FT lens. Therefore, the radiated far-field can be obtained as

$$\begin{aligned}E(\theta)=\sum_{n=0}^{N}&\int_0^A 2A_m(r)A_r(r)J_o(2\pi nrd_1/\lambda_0F)rdr\\&\cdot f_n(\theta)\exp[j(nkd_{RF}\sin\theta-2\pi nd_1r_o/\lambda_0F)\end{aligned}\quad,\tag{1.7}$$

where J_0 is the zeroth-order Bessel function.

When the size of the incident light source is reduced, a narrower beam-width antenna beam will be obtained from the numerical calculation of (1.7) as shown in Fig. 1.3, here, we assume that the input light source is a truncated Gaussian beam, $f_n(\theta)$ is a cosine function and the radius A is equal to the Gaussian beam-width ω_o. However, a smaller incident light source will produce a larger beam-width beam in the object plane of the FT lens; therefore, less optical power will be sampled, and this will cause smaller antenna gain when the same element-number array antenna is employed. The half-power beam width (HPBW) of the array antennas is shown in Fig. 1.4. This graph indicates that, when the number of array elements is large enough, the antenna beam width is not only decided by the antenna size but also greatly depends on the size of the light source on the object plane of the FT lens in the optical processor. From Fig. 1.5, we can see that as focal length F of the lens decreases, the main lobe widens and the side lobe level increases as well. We also find that as the optical sampling spacing d_l reduces to half value, the same effort can be seen as the reduction of ω_o in Fig.1.3. This means that the arrangement of sampling elements in the image plane can also control the antenna beams. All of these features are very different from the conventional beam forming networks used for microwave array antennas.

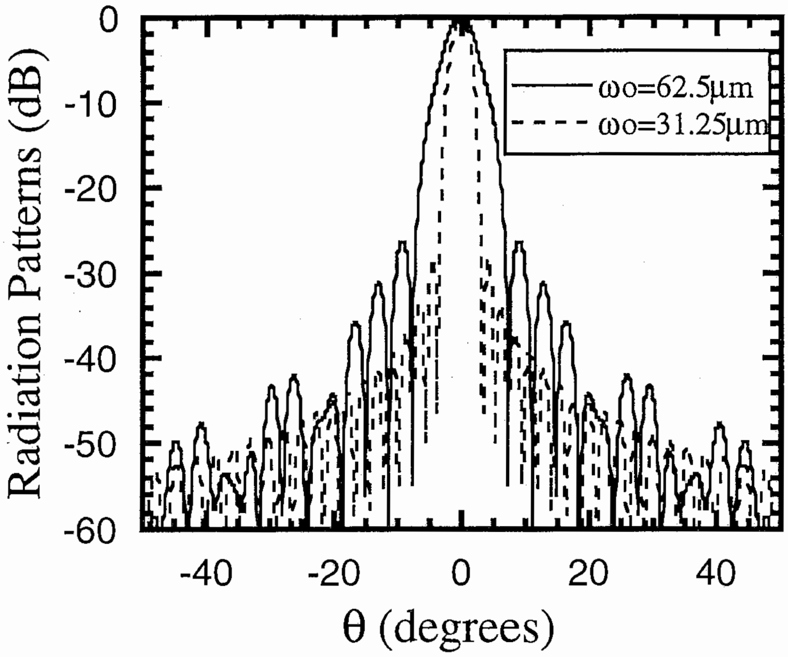

Fig.1.3 40-element half-wavelength spacing array antenna beams controlled by size of input optical beam-width (F=120mm, d_1=125 μm)

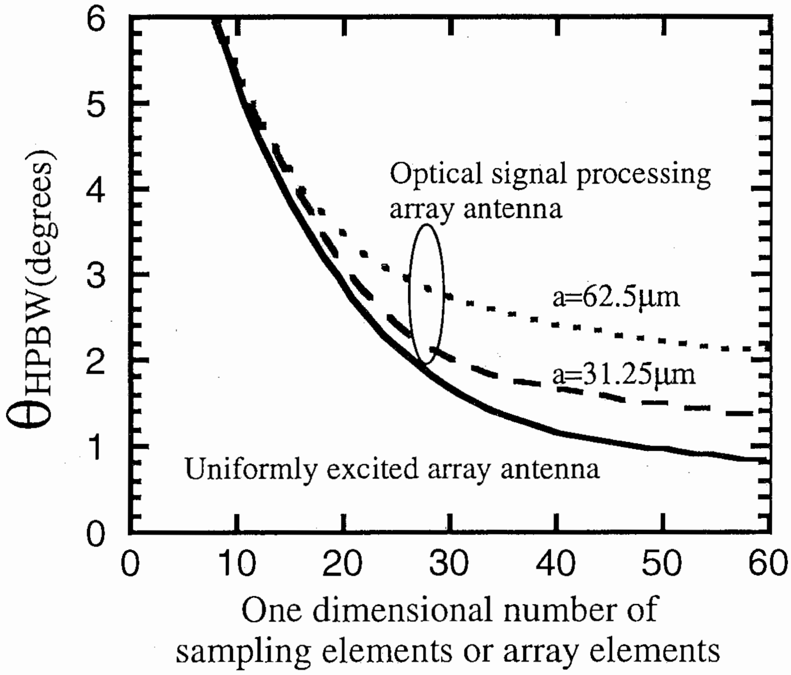

Fig.1.4 Half-Power Beam Width (HPBW) of antenna radiation patterns versus number of array elements and incident optical beam radius

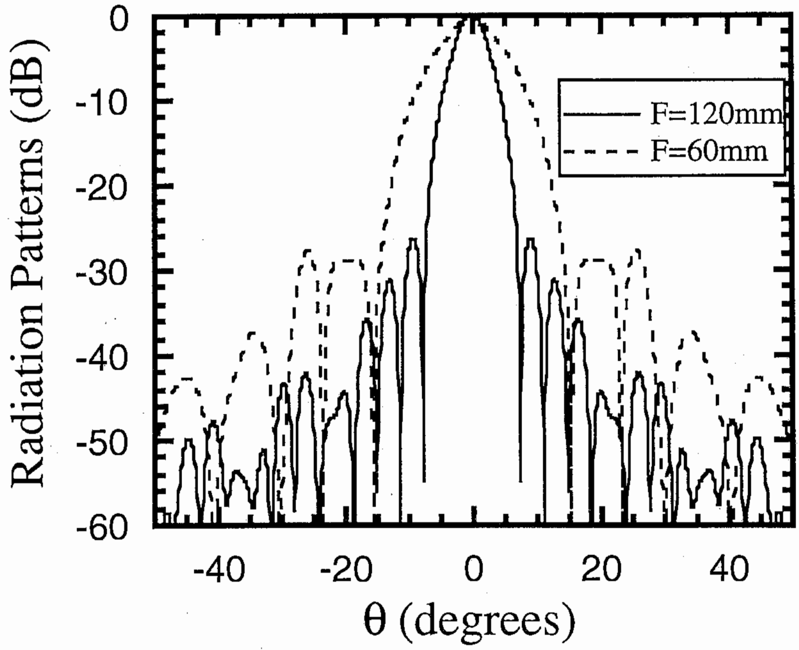

Fig.1.5 40-element half-wavelength spacing array antenna beams controlled by focal length of FT lens (d_1=125 μm, ω_o=62.5μm)

C. Optical Power Sampled by Optical Element Array

Since optical signal processing by the FT lens is implemented spatially, the optical power loss during sampling by an optical element array must be discussed.

By combining two identical beam-waist perfect Gaussian beams emitted from lasers with power Pmo and Pro, respectively, the power received by a photodetector through an optical sampling element placed at (x_u, y_v) in the image plane with radius *a* can be expressed by

$$\begin{aligned} P_{u,v} &= \int_0^{2\pi}\int_0^a 2A_{mo}A_{ro}\left(\frac{\omega_o}{\omega_1}\right)^2 e^{-2[r_1^2-2r_1d_1(u\cos\theta+v\sin\theta)+d_1^2(u^2+v^2)]/\omega_1^2} r_1dr_1d\theta \\ &= \int_0^{2\pi}\int_0^a \frac{4\sqrt{P_{mo}P_{ro}}}{\pi\omega_1^2} e^{-2[r_1^2-2r_1d_1(u\cos\theta+v\sin\theta)+d_1^2(u^2+v^2)]/\omega_1^2} r_1dr_1d\theta \end{aligned} , \quad (1.8)$$

where $A_{mo}(or\ A_{ro}) = \sqrt{2P_{mo}(or\ P_{ro})/(\pi\omega_o^2)}$.

If the size of sampling elements is small enough, the power received by a sampling element can be expressed by an averaged form as

$$P_{u,v}(r_1) = \sqrt{P_{mo}P_{ro}}\frac{2a^2}{\omega_1^2}e^{-2(x_u^2+x_v^2)/\omega_1^2}. \tag{1.9}$$

The total illuminating active optical power in the image plane can be calculated by an integration of the Gaussian field distribution over the whole space as

$$\begin{aligned} P_t &= \int_0^{2\pi}\int_0^{\infty} 2A_{mo}A_{ro}\left(\frac{\omega_o}{\omega_1}\right)^2 e^{-2r_1^2/\omega_1^2} r_1 dr_1 d\theta \\ &= \pi\omega_o^2 A_{mo}A_{ro} = 2\sqrt{P_{mo}P_{ro}} \end{aligned} \tag{1.10}$$

The active power ratio between total sampled power by an $N_u \times N_v$ sampling element array and total power in the image plane can be defined by

$$\eta = \frac{\sum P_{m,n}}{P_t}. \tag{1.11}$$

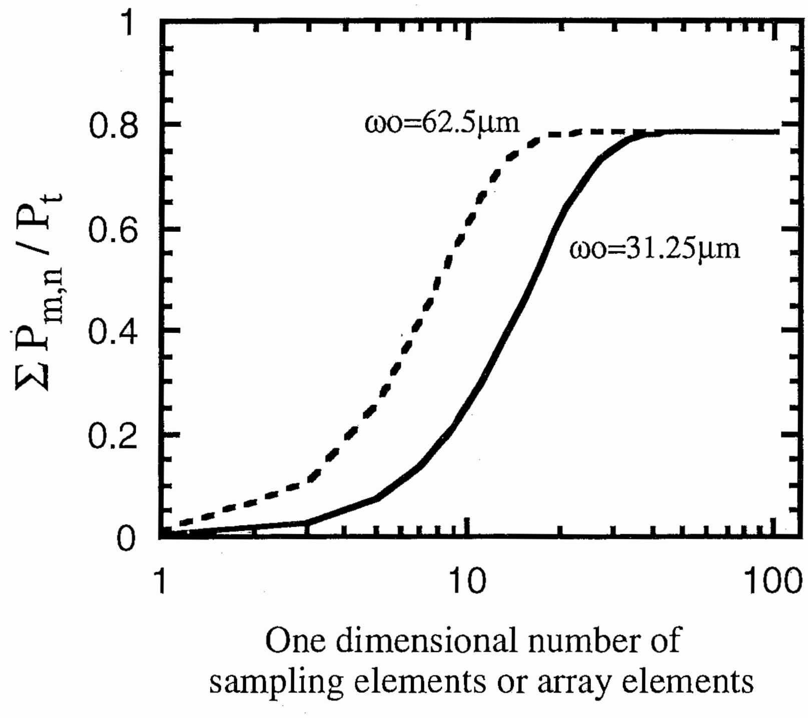

Fig.1.6 Ratio between total sampled power by optical sampling element array and total active power in image plane of FT lens

The numerically calculated ratio is shown in Fig. 1.6, where ω_o=62.5 μm and 31.25 μm, λ_c=1.3 μm, F=120 mm and d_s =125 μm. Here, the optical sampling elements could be optical fibers or optical waveguides that are placed as a array without spacing between them. We can see that when the number of sampling elements reach some value, i.e., effective number, the sampling power efficiency will reach almost 80%, and no more power will be sampled by the optical sampling element array and feed the antenna. We also find that when the size of the input light source becomes small, the power in the image plane will concentrate in a bigger area, then larger effective number of sampling elements is required.

By comparing Figs. 1.4 and 1.6, it can be seen that to maintain both good sampling power efficiency and beam shaping capability in the optical domain, the most suitable one-dimensional number of sampling elements should be between 30 and 40.

1.3. MULTIBEAM GENERATION BY OPTICAL SIGNAL PROCESSING TECHNIQUES

A. Multibeam Array Antenna Configuration

Recently, there has been considerable interest in the development of multiple beam array antennas for application to satellite-on-board antennas [11], [12] and mobile communication base stations.

We propose a new type of optical signal processing feed for multibeam microwave array antennas. Only one Fourier transform lens is employed to perform the parallel optical signal processing spatially and produce a large number of multiple beams (Fig. 1.7). Here, the fiber connected to the reference laser is placed on the optical axis, and the fibers connected to master lasers are placed around it. This design will greatly reduce optical alignment difficulties, free-space transmission loss, and size of the optical processing feed part.

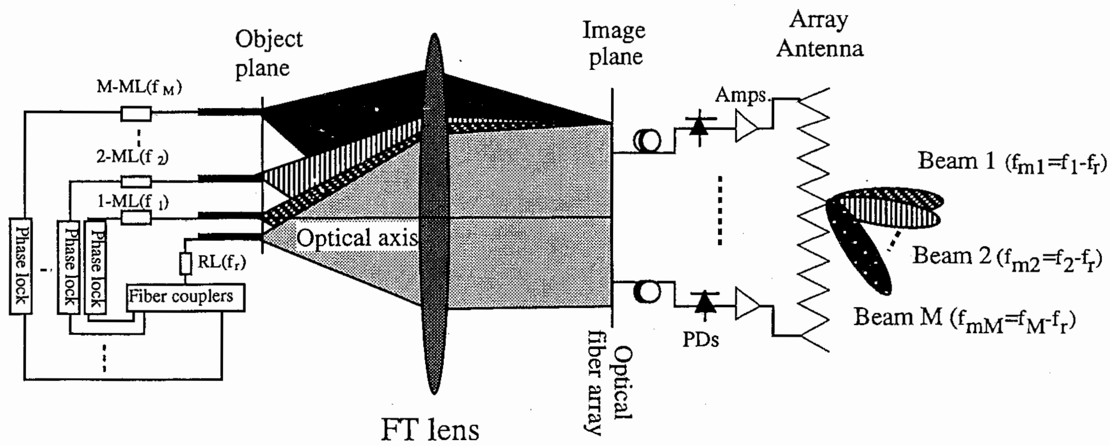

Fig.1.7 Configuration of proposed optical signal processing multibeam array antenna

Since the various arrangements of input laser beams on the object focal plane of the FT lens can control the antenna radiation characteristics as shown in section 1.2(B), if we place *M* optical fibers connected to *M* master lasers as signal sources with different frequencies f_{o1}, f_{o2}, ..., f_{oM} in this object plane, and lock the laser sources to a reference laser with individual frequency offsets, multiple beams from array antenna will be produced with individual microwave (RF) frequencies f_{RF1}, f_{RF2}, ..., f_{RFM} as shown in Fig. 1.7.

To increase the antenna gain and reduce the antenna covering open space, the generation of multiple overlapping beams is necessary. Because of the structure of standard single-mode optical fiber in which the diameter of core is only 10 μm compared with 125 μm of cladding, simply placing the optical fibers in the focal plane of the FT lens cannot produce overlapping antenna beams. To solve this difficulty, a GIF lens is employed to connect to the incident emitting fibers so that the small beam-spots will expand to large contiguous beams in the focal plane and a plane wave front is maintained as shown in Fig. 1.8.

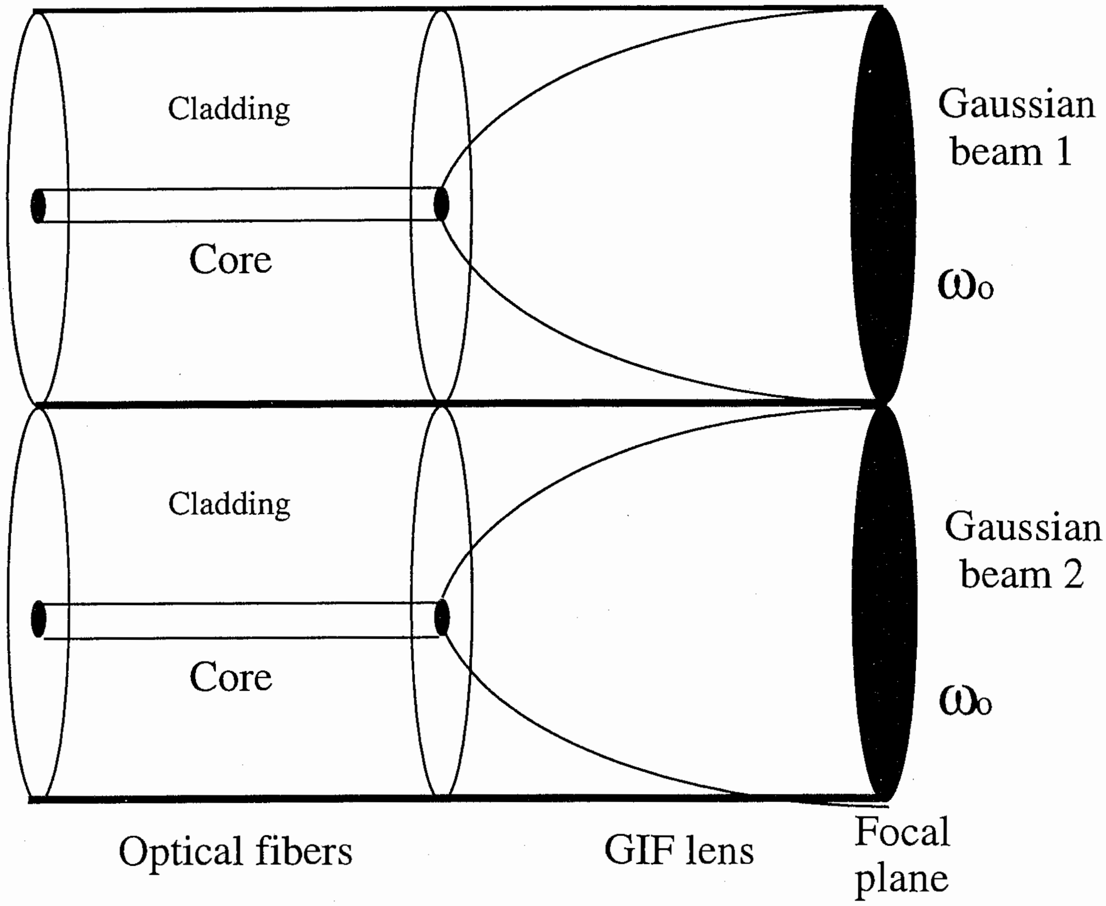

Fig.1.8 Expansion of Gaussian beam in object plane of FT lens

Fig. 1.9 shows how three Gaussian beams (the one on the axis is the reference beam and the others are master beams) transmit to a focusing lens and mix in the right-side (image) plane. In this figure, d_o and d_I indicate the distance between two adjacent emitting fiber centers and the distance between two adjacent sampling element centers, respectively. The dashed lines inside the solid Gaussian distribution are the moving sinusoidal interference patterns.

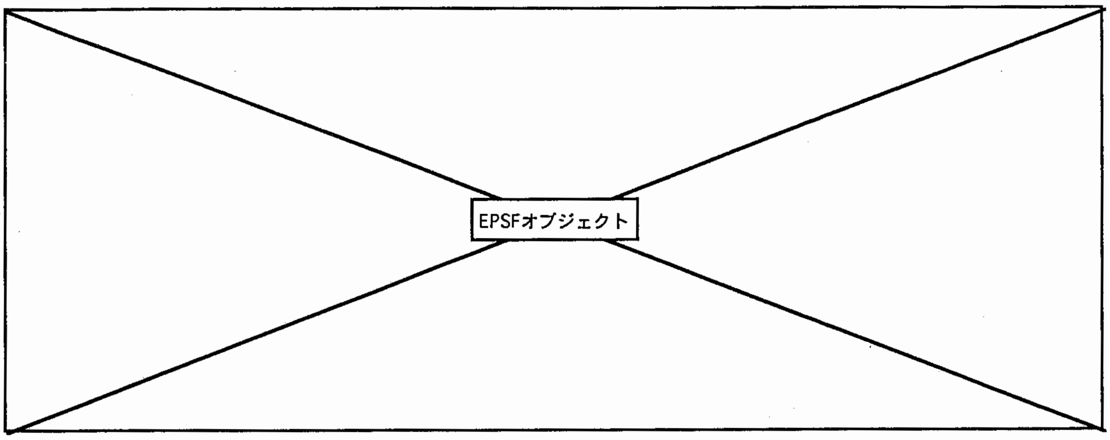

Fig.1.9 Parallel optical signal processing of Gaussian beams by focusing lens

B. System Parameter Analysis

(a) RF excitation for antenna elements by optical heterodyne

When multiple x-directed optical beams from plural input laser fibers in the object plane emit to the optical processor, the total field in the image plane of the FT lens is

$$\begin{aligned}\vec{E}_T &= \vec{E}_{m1} + \vec{E}_{m2} + \cdots + \vec{E}_{mM} + \vec{E}_r \\ &= \vec{i}_x (A_{m1} e^{j\Omega_{m1}t + jk_o \sin\theta_{m1} r_1} + A_{m2} e^{j\Omega_{m2}t + jk_o \sin\theta_{m2} r_1} + \cdots + A_{mM} e^{j\Omega_{mM}t + jk_o \sin\theta_{mM} r_1} + A_r e^{j\Omega_r t + jk_o \sin\theta_r r_1})\end{aligned} \quad (1.12)$$

After sampling by a fiber array, the total optical field intensity at the photodetector can be obtained as

$$\begin{aligned} I &= \vec{E}_T \cdot \vec{E}_T^* \\ &= \sum_{i=1}^{M} A_{mi}^2 + A_r^2 \\ &+ \sum_{i=1}^{M} 2A_{mi}A_r \cos[\Omega_{RFi}t + k_o(\sin\theta_{mi} - \sin\theta_r)r_1] \\ &+ \sum_{l=1}^{M} \sum_{i=2,i\neq l}^{M-1} 2A_{m1}A_{mi} \cos[\Omega_{mli}t + k_o(\sin\theta_{ml} - \sin\theta_{mi})r_1] \end{aligned} \quad (1.13)$$

The first line in Eq. (1.13) is the dc-part. The multiple RF frequency responses which will be the antenna working frequencies and produce multiple beams is due to the second line. The other parts of Eq. (1.13) generate unexpected signals between master laser beams, but they can be cut off by an RF filter after the photodetection.

(b) Radiation angles of multiple beams

Since the directions of radiated microwave beams from an array antenna can be controlled by the positions of input fibers (Fig. 1.7), the antenna beam radiation angle for m-th beam can be obtained by

$$\theta_m = M_a \frac{md_o}{F}, \tag{1.14}$$

where M_a is the beam magnification defined as $M_a = \frac{d_1}{\lambda_o} / \frac{d_{RF}}{\lambda_{RF}}$.

(c) Maximum number of multibeam and maximum number of antenna elements

Although no specific design condition for sampling elements is required for sampling the optical field distributions, picking up the RF signals equal to the moving interference pattern rate requires that at least one optical sampling element be placed between each null of the interference pattern. Therefore, we have a condition for the optical feed parameters

$$\frac{d_1 r_o}{F} \le \frac{\lambda_o}{2} \quad , \tag{1.15}$$

where r_0 denotes the location of the fibers emitting the master laser beams.

Accordingly, the maximum number of multiple beams in one dimension that can be produced by the microwave array antenna will be determined by

$$M = \frac{2r_{o\max}}{d_o} = \frac{\lambda_o F}{d_o d_1}. \tag{1.16}$$

Since most optical power concentrates in the beam waist of the Gaussian beam, the element number of both sampling element array and microwave antenna array can be evaluated approximately by

$$N = \frac{2\omega_1}{d_1} = \frac{2\lambda_o F}{\pi d_1 \omega_o}. \tag{1.17}$$

The maximum number of multiple beams and the maximum number of optical sampling elements or antenna elements are plotted against the optical sampling spacing and focal length of the focusing lens in Figs. 1.10 and 1.11, respectively. These graphs indicate that the number of multiple beams and the antenna size can be increased greatly by integrating a sampling fiber array to an optical waveguide array.

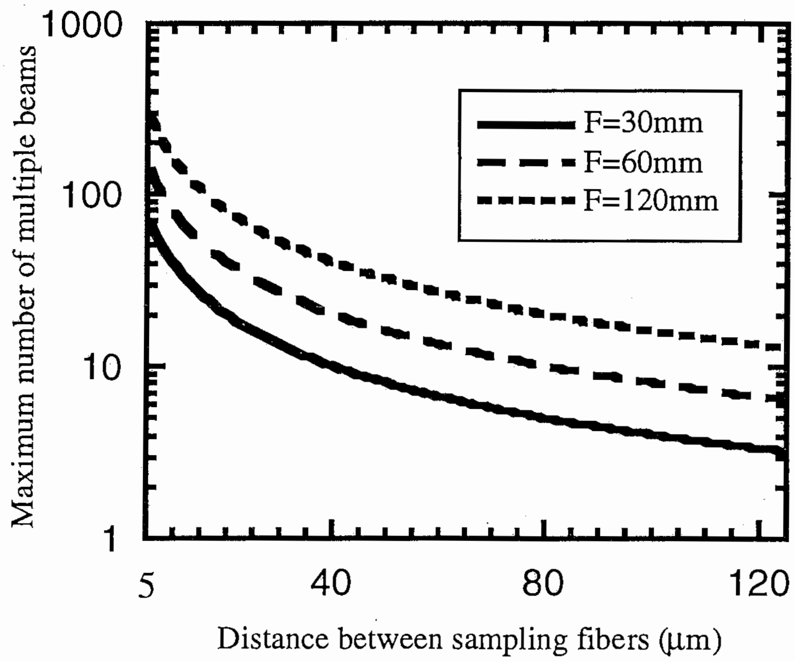

Fig.1.10 Maximum number of multiple beams versus optical sampling spacing and focal length of focusing lens (λ_o=1.3μm, d_o=2ω_o=125μm)

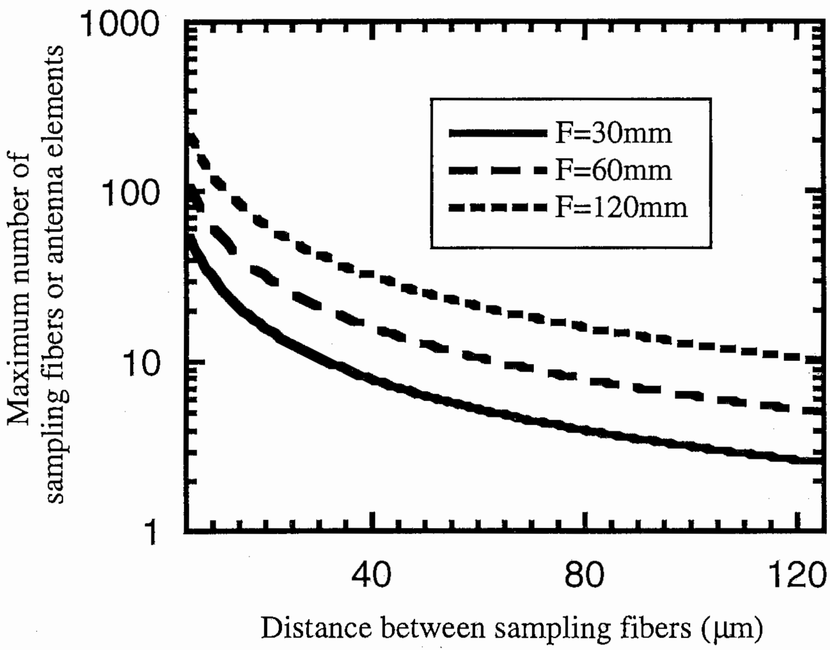

Fig.1.11 Maximum number of sampling elements or antenna elements versus optical sampling spacing and focal length of focusing lens (λ_o=1.3μm, $d_o=2\omega_o$=125μm)

1.4. EXPERIMENTAL PERFORMANCE OF THE OPTICAL PROCESSING FEED

A. Experimental Setup

The experimental setup for the two-beam optical signal processor is shown in Fig. 1.12. Three GIF lens rod single-mode fibers, connected to three LD pumped Nd:YAG tunable lasers in the 1.319 μm region with output power of roughly 50 mw, were fixed without spacing in parallel in the object plane of an FT lens. Therefore, the distance between two adjacent fibers is d_o=125 μm. Two master lasers were separately phase-locked to a reference laser with frequency offsets 14.8 GHz and 15 GHz. Three laser beams were transmitted through a focusing lens, mixed spatially, and then sampled by a lenslet scanning optical fiber. By using high-speed photodetectors (NEL KEPD1510VPG) with 40 GHz maximum RF response, the spectra of relatively high-level multiple RF signals in the Ku band were obtained (Fig. 1.13). To create an RF signal phase reference, another fixed sampling fiber was used. Fig. 1.14 shows the stability of the measured RF signal at 14.8 GHz, which only has 3^0 deviation in phase and 0.4 dB deviation in amplitude.

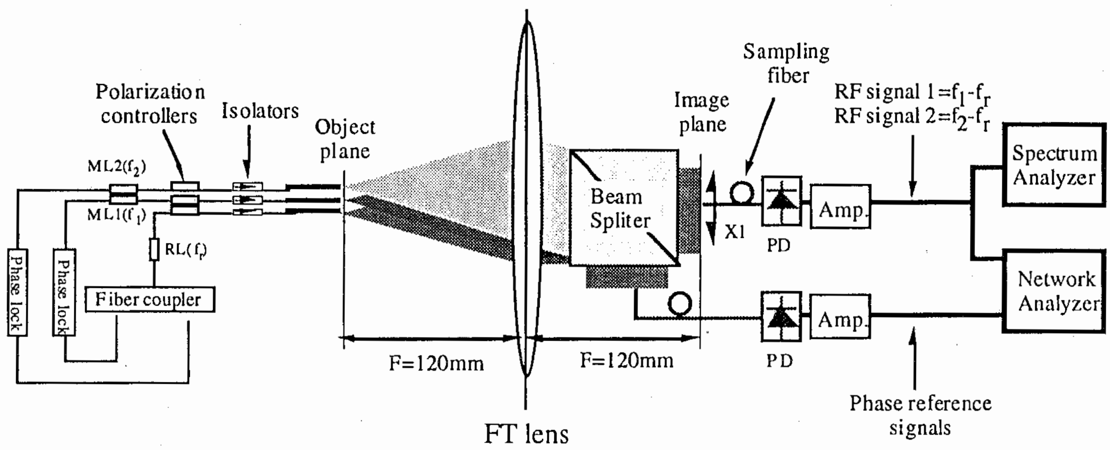

Fig.1.12 Experimental setup of optical processor for 2-beam microwave array antennas

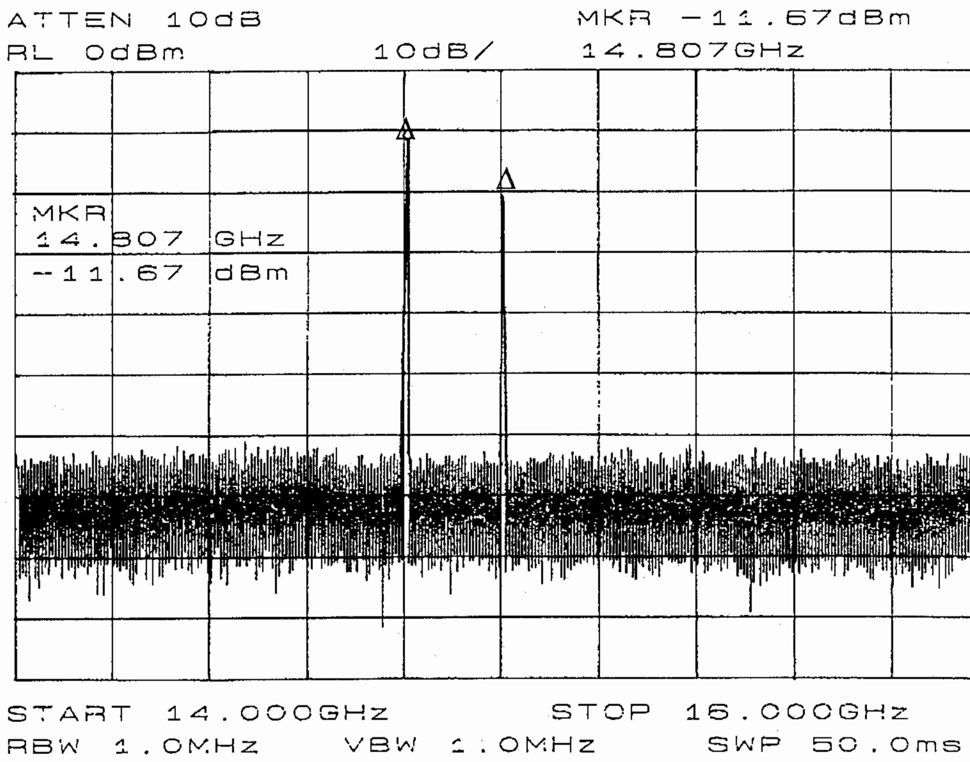

Fig.1.13 Detected RF signals at 14.8 GHz and 15 GHz from sampling fiber

As mentioned in the discussion on the optical heterodyne techniques in section 1.2(A), to obtain the maximum value of RF signals by mixing two coherent light beams spatially, the electric field of the incident optical beams should be linear-polarized in the same direction. Therefore, when we set up the experimental system, polarization controllers were used to generate linear polarization optical beams, and optical stages with rotational fiber holders were used to achieve the same-direction polarization of optical beams. Optical isolators were also introduced in this experimental setup to reduce the reflection when optical beams emit to free space from optical fibers.

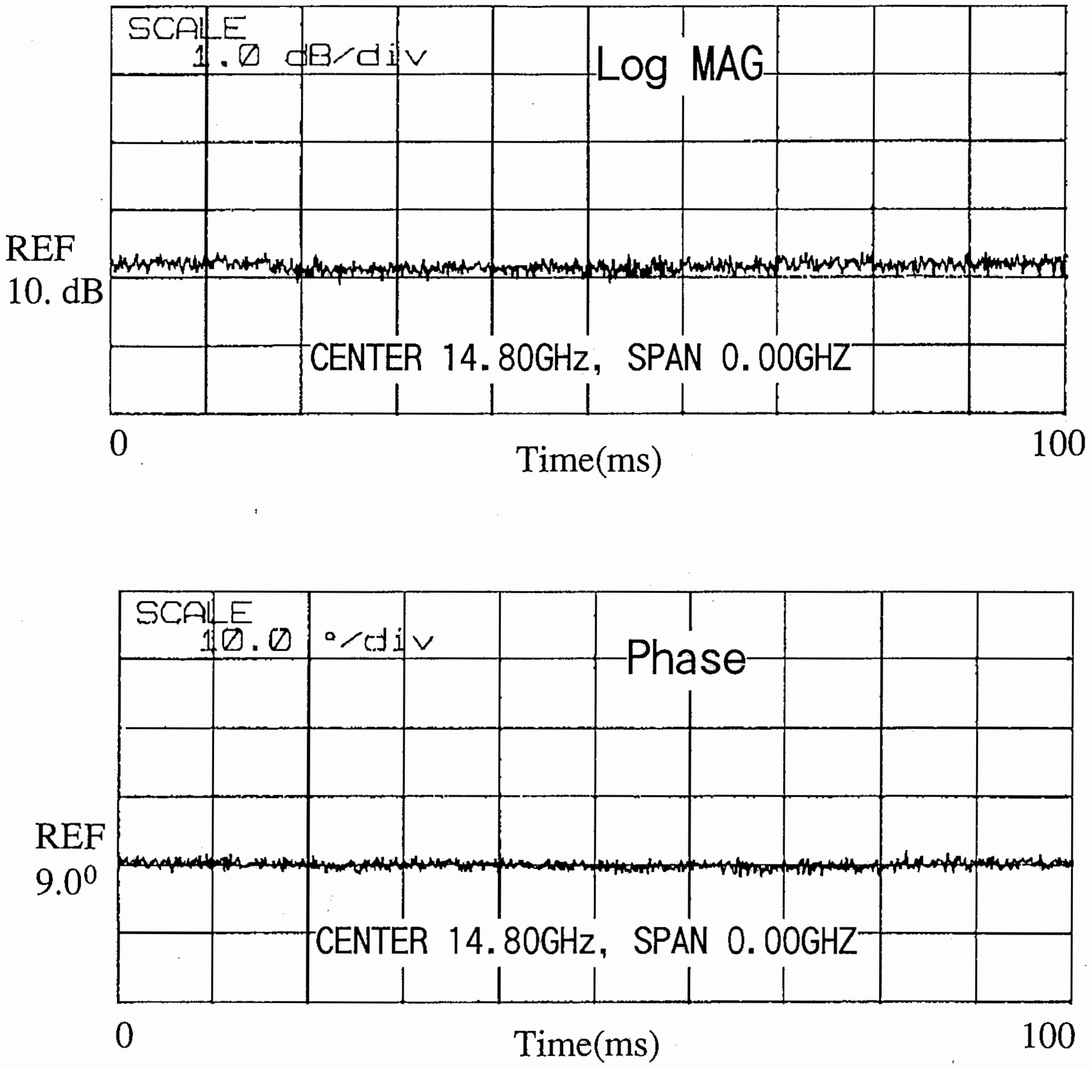

Fig.1.14 Stability of measured RF amplitude and phase at 14.8 GHz

B. Experimental Results

The amplitude and phase distributions of multiple RF signals at 14.8 GHz and 15 GHz in the image plane of the Fourier transform lens were sampled by a lenslet fiber controlled by an optical auto-stage and measured by a Network Analyzer (HP8510C). The measured amplitude and normalized data in comparison with the calculated Gaussian distribution are shown in Fig. 1.15. The measured phase and the difference between two phase distributions are shown in Fig. 1.16. The linear phase difference indicates that beams radiating in two different directions can be obtained. Based on the measured amplitude and phase distributions, the calculated far-field radiation patterns of a half-wavelength spaced 20-element array antenna are shown in Fig. 1.17. This figure shows that perfect overlapped multiple beams can be obtained, and the agreement between the measurement-based data and the pure calculations from Eq. (1.6) is quite good.

In this proof-of-concept experiment, two individual master lasers were employed to generate two different RF frequency beams. However, this will be modified in the near future by one low-noise laser with multiple modes. This is expected to reduce the cost of this optical feed.

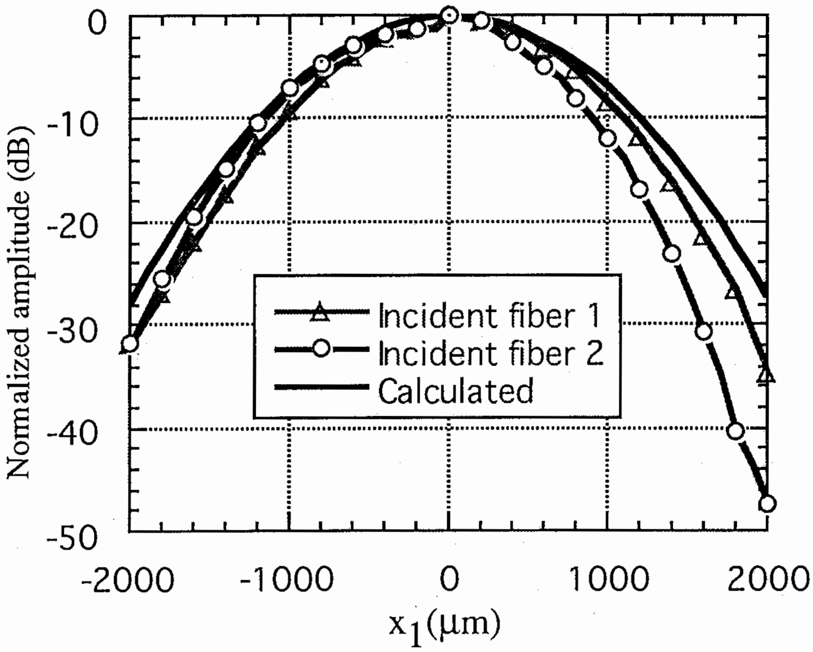

Fig.1.15 Measured amplitude distribution of multiple RF signals

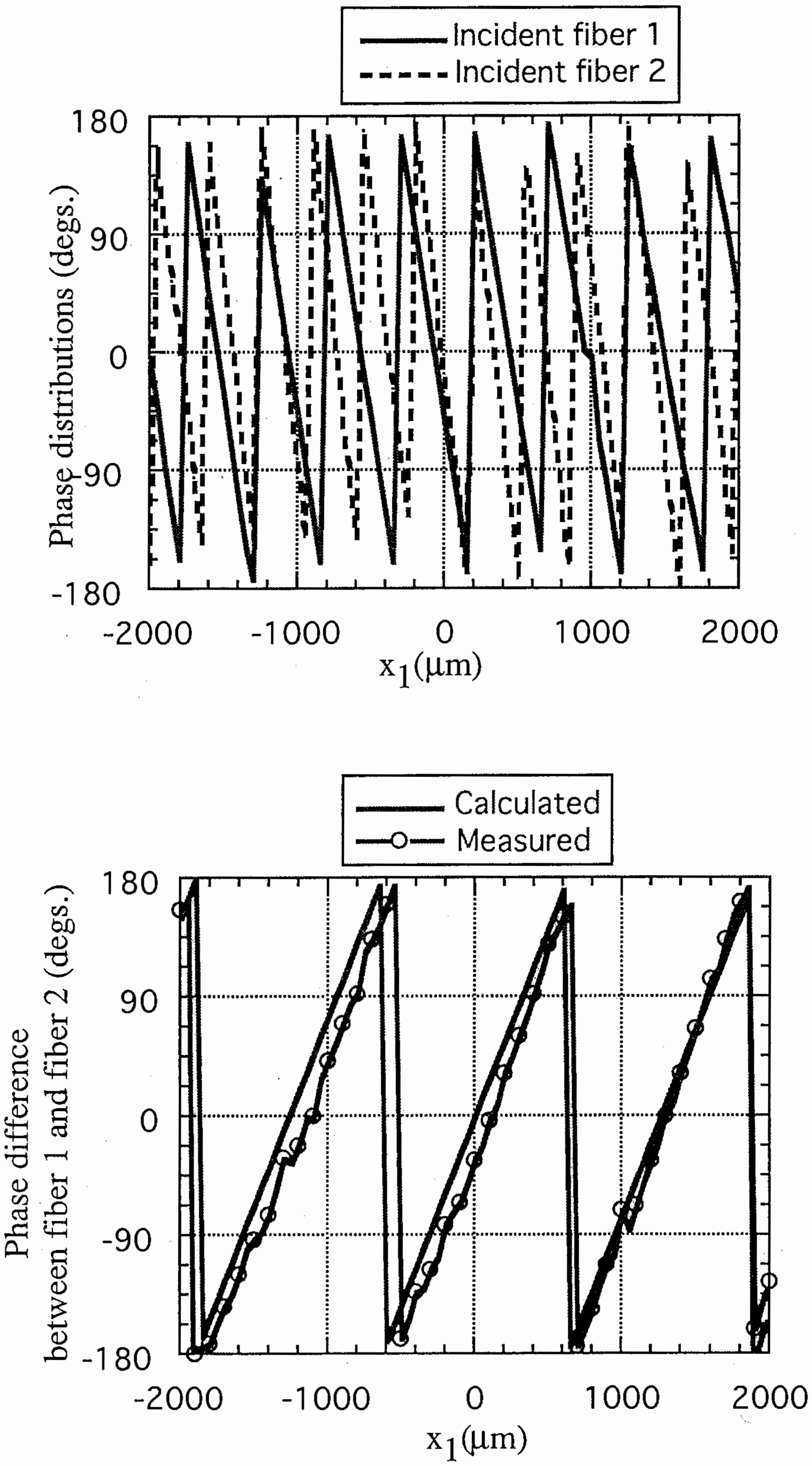

Fig.1.16 Measured phase distribution of multiple RF signals

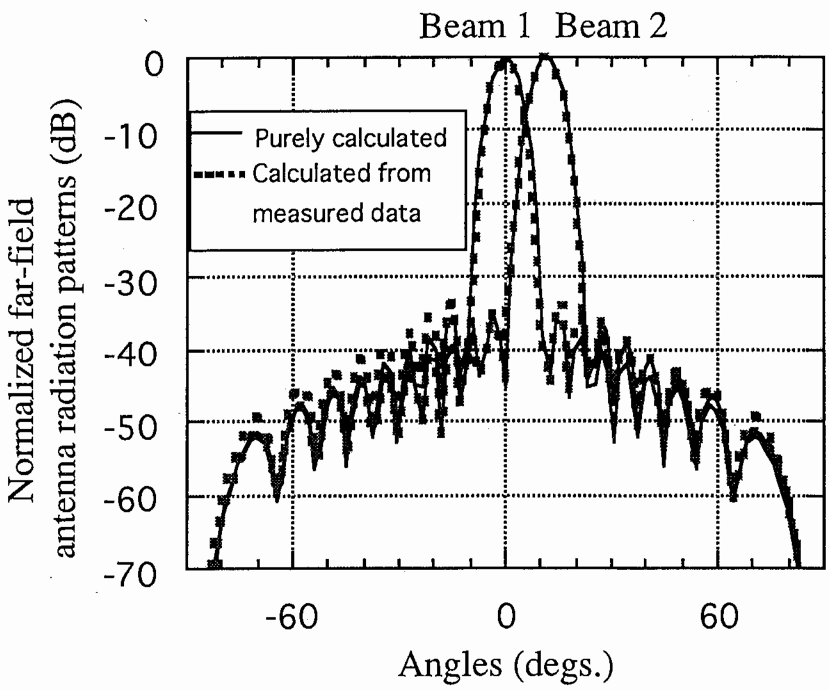

Fig.1.17 Calculated array antenna far-field radiation patterns from measured array excitation field (antenna is a half-wavelength spacing, 20-element linear array)

1.5. CONCLUSION

In this Chapter, an optical signal processing multibeam microwave array antenna has been described. By placing optical fibers as signal sources in the object focal plane of the FT lens and phase-locking the laser sources to the reference laser with individual frequency offset, multiple beams from an array antenna can be produced with individual RF frequencies. This optical processor implements the division, interconnection and combination of light spatially, and is expected to greatly reduce the size and complexity of BFN systems. Based on optical heterodyne processing and Fourier-optical principles, a system design and analysis method have been established.

The experimental system for a two-beam array antenna was designed and demonstrated. By mixing the beams from two master lasers and a reference laser with fixed frequency offsets, two RF signals in the Ku band with different phase distributions and the same Gaussian intensity distributions were detected and measured spatially. There was a very good agreement between the simulated and measured results.

Our work shows that the Fourier optical processor provides feasibility and various capabilities and for array antenna beam formation. This optical processor can offer diverse functions to telecommunication applications with its ultrawide band and high-stability RF signals.

Chapter 2

Receive Mode of Optical Signal Processing Multibeam Array Antennas

2.1. INTRODUCTION

Array antenna with a flexible Beam Forming Network (BFN) for the control of individual elements (radiators) is used widely in radar, satellite and mobile communications as a most versatile type of antennas. Since both antenna and optical processing share the common technique -- Fourier analysis, the application of optical engineering to array antennas becomes possible. Recently, because of the progress of modern photonics [1], many successful optically controlled BFN systems and even array antenna systems have been demonstrated for beam steering [7], [14], [15], beam shaping [8] and multibeam operation [9].

However, so far there are only very few papers discussing the receive mode of the optical processing array antennas, especially for the multibeam operation [2], [16]. The reason is that the phase information of the received RF multiple beams is difficult to maintain in the optical fibers which are main parts in the optical BFN.

In this Chapter, we will introduce the concept and experimental examination of the receive mode of the optical processing multibeam array antennas. In this receive mode, the generated RF signals by optical processor will be shifted as LO signals, and the received RF beams will be discriminated in the downconverted IF frequency domain by a mixer array between optical processor and antenna elements. In this configuration, it is not neccessary to convert the phase information of arrived RF signal to the optical domain.

2.2. OPTICAL SIGNAL PROCESSING MULTIBEAM ARRAY ANTENNA

It is well-known that the far-field radiation field and the antenna aperture distribution is a pair of Fourier transform (FT), and an optical lens also can perform the FT by using its object and image planes. Therefore, an optical lens can be employed as a BFN processor to implement the beam forming for an array antenna. In this optical processor, the generation, distribution and processing of microwave signals which will be the array antenna operating frequencies and will be obtained by photodetection can be realized in the optical domain [2].

The optical signal processing array antenna for transmission is shown in Fig.1.7. In this optical processor, plural input optical fibers connecting to individual master lasers in the object focal plane of FT lens are emitting different wavelength optical beams. By mixing these optical beams with a reference laser which is phase-locked to maser lasers, the frequency offsets between master and reference lasers will be detected as array antenna working microwave frequencies by a photodetector array after an optical sampling in the image focal plane of FT lens. The directions of microwave beams radiated from the antenna are determined by the location of input optical fibers as discussed in Chapter 1.

We have demonstrated a successful proof-of-concept experimental setup of the optical processor for two-beam array antennas as shown in Chapter 1[13]. In this experiment, relative high power (50mW), low noise (<0.05%rms, 5Hz-10MHz), narrow linewidth (<5KHz) and tunable LD pumped Nd:YAG lasers were used. Obtained RF signals from the optical processor have maximum power level of -6 dBm, and their phase and amplitude fluctuate within 3^0 and 0.4 dB, respectively, due to the spatial air vibration and nonlinear response of the GaAs amplifiers. These relative high level and stable RF signals can be used to be LO signal as the inputs of the T/R modules in the receive mode of antennas which will be introduced in next Chapter. The measured phase of RF signals have expected distributions which will generate microwave multiple beams in different directions.

2.3. RECEIVE OPERATION FOR THE ARRAY ANTENNAS

In a receiving microwave antenna, usually, the local oscillator (LO) pumping to the mixer stage of all the receivers is introduced for the frequency conversion, and the beam formation is performed in the RF or IF domain. Usually the LO signal is a pure, unmodulated sinusoid. But there is no reason why the LO can not be beamformers via a signal distribution network or BFN. Here we propose a novel configuration for multiple beams reception by using plural LO signals generated by the same optical processor as used in the transmit mode of antenna. Therefore, large number of variable phase distribution LO signals can be produced by the tunable lasers in the optical processor. Such large number of LO signals are quite difficult to generate simultaneously by using RF techniques.

As the receive mode of the optically controlled array antennas, Koepf [2] proposed a configuration for a single beam reception, and Shibata et al [16] proposed a spatial multibeam discrimination method. Here we will describe a new structure for the received multibeam discrimination in the frequency domain.

As described in Section 2.2, the optical beam forming network feed for multibeam array antennas consists of a Fourier transform lens, M master lasers and a reference laser which are phase-locked each other. The transmitting microwave signals are generated by the frequency-offsets between master lasers and a reference laser. As a receive mode of the antenna, the optical feed shifts the microwave frequency to the LO frequency, and a mixer array is introduced between the output of optical processor and array antenna elements. Therefore, the received RF signals are downconverted to IF signals, and only the IF signals whose phase gradient is matched to that of LO signals can be maximally summed by the IF combiner before entering the receiver. The configuration of the antenna receive mode is shown in Fig. 2.1 and the basic principle can be proved as followings.

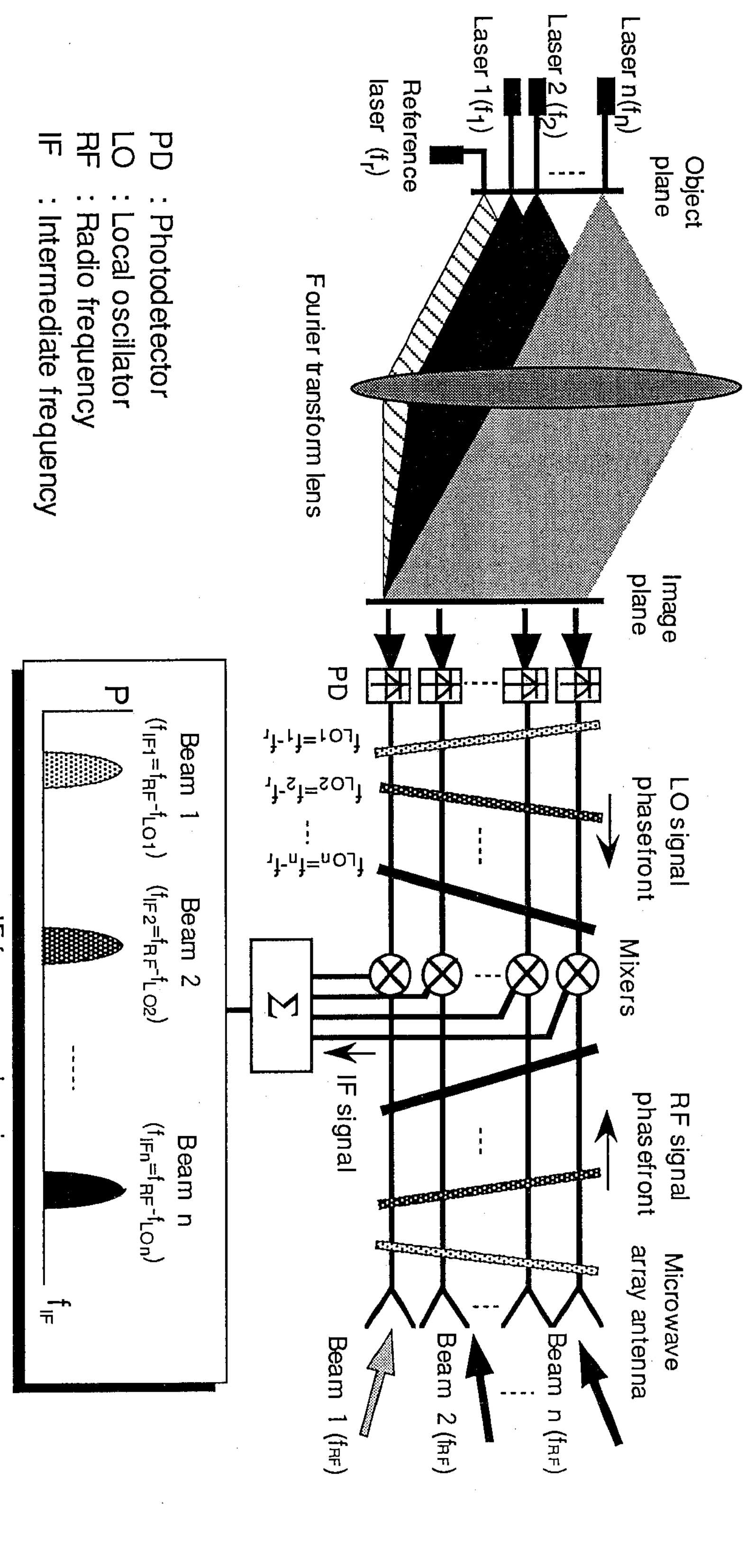

Fig. 2.1 Configuration of the receive mode

For arbitrary beam m, the RF signals received by arbitrary equispaced linear antenna element n are given by

$$E_{Rmn} = Ae^{-j\omega_{Rm}t-jn\beta_m} , \quad (2.1)$$

and the LO signals generated by the optical signal processing feed are given by

$$E_{Lmn} = Be^{-j\omega_{Lm}t-jn\alpha_m} . \quad (2.2)$$

Therefore, the IF signals generated by a microwave mixer can be written as

$$E_{IFmn}=ABe^{-j(\omega_{Rm}-\omega_{Lm})t-jn(\alpha_m-\beta_m)} \quad (2.3)$$

where A and B represents applied elemental amplitude weights; ω_{Rm} and ω_{Lm} are the frequencies of RF signals received by antenna and LO signals generated by the optical processor; and α_m and β_m are the phase-steps of RF and LO signals with the same phasefront, respectively.

Considering only the first-order difference frequency output of mixers and the case of constant A and B, the summation of these IF signals in Eq.(2.3) for beam m will be combined by an IF power combiner as

$$\begin{aligned} E_{IFm} &= ABe^{-j\omega_{IFm}t}\sum_{n}^{N-1} e^{jn(\alpha_m-\beta_m)} \\ &= ABe^{-j\omega_{IFm}t}\frac{1-e^{-jN\sigma_m}}{1-e^{-j\sigma_m}} \\ &= ABe^{-j\omega_{IFm}t-j(N-1)\sigma_m/2}\frac{\sin N\sigma_m/2}{\sin\sigma_m/2} \end{aligned} \quad (2.4)$$

where $\omega_{IFm} = \omega_{Lm} - \omega_{Rm}$ is IF band frequency, and $\sigma_m = \alpha_m - \beta_m$ is the phase-step of IF signals.

We note that the maximum of fractional part in Eq. (2.4) is N, when $\sigma_m = l \bullet 2\pi$, where $l = 0,\ 1,\ 2,\ \cdots$. Since we only consider the case when the array element spacing is less than one-half wavelength, then $l \geq 1$ becomes invisible region. Therefore the maximum value of the IF signal power sum only appears when the phases of the RF and LO signals are equal. Consequently, the same frequency IF outputs from all mixers shoud be in phase for a signal receiving at the array antenna from a particular direction, and will produce a miximum output from the IF combiner at a particular RF frequency. Signals arriving from other directions will produce less output at this RF frequency, and may produce greater output at other frequencies, which correspond to other phase-matched LO signals.

When the same frequency multiple beams are received from different directions, the beams can be discriminated separately in the frequency domain by using different frequency and different phase distributions of LO signals which are created by optical processor, and the directions of beams can be recognized by the location of incident laser fibers in the optical processor. By using other RF paths over the mixers or a T/R module, the same optical processor can be used for both transmit and receive mode. However, as shown in Fig. 2.1, since the phase distributions of LO and RF signals have opposite gradients as to obtain in-phase IF signals in the receive mode, the direction of received beams will become opposite to that of transmitting beams.

2.4. FREQUENCY ARRANGEMENT

For multibeam receive operation of array antennas, since the transmission lines between optical processor an array elements are commonly used for plural RF and LO signals with different phase gradients and the nonlinear characteristics of mixers will cause unexpected harmonic frequencies, in general, the mixer generates output frequencies that satisfy the relation

$$f_{IF} = pf_L + qf_R \qquad \text{for single beam} \qquad (2.5a)$$

$$f_{IF} = \sum_{m=1}^{M} (pf_{Lm} + qf_{Rm}) \qquad \text{for multiple beams} \qquad (2.5b)$$

where $p,\ q = 0,\ \pm 1,\ \pm 2,\ \cdots$. Although the spurious frequency responses can be filtered effectively by band-pass filters, the best way to avoid spurious responses is the careful frequency arrangement of RF, LO and IF signals. Therefore, the received RF multiple beams can be discriminated in the downconverted IF frequency domain, after the IF power combiner and filters, by the proper choice of tunable LO signals generated in the optical processor. According to the cases of received RF beams, we will consider the following two catalogues of LO frequency arrangement.

(1) When different frequency RF beams are received from different directions, obtained IF frequency difference of f_{Rm}-f_{Lm} should be smaller than other spurious responses as

$$f_{IFm} \leq \left|f_{RFi} - f_{LOj}\right|,\ \left|f_{LOi} - f_{LOj}\right|,\ \left|f_{RFi} - f_{RFj}\right|,\ i,\ j = 0,\ 1,\ 2,\cdots,\ m,\cdots,\ M \tag{2.6}$$

Therefore, the expected IF signals will be the smallest group in the downconverted frequency domain, and the unexpected spurious response will be rejected by high-band-pass filters as shown in Fig. 2.2(a).

Otherwise, the spectrum groups of RF and LO signals should be separated enough comparing to f_{IF}, and a band-pass filter will be used after the IF power combination as will be shown in case (2).

(2) When the same frequency RF beams are received from different directions, obtained IF frequency should be larger than other spurious responses as

$$f_{IFm} \geq \left|f_{RF} - f_{LOj}\right|,\ \left|f_{LOi} - f_{LOj}\right|,\ \ j = 1,\ 2,\cdots,\ m,\cdots,\ M \tag{2.7}$$

And, the expected IF signals will be the largest group in the downconverted frequency domain, and the unexpected spurious response will be rejected by low-band-pass filters as shown in Fig. 2.2(b).

The mixers used here should be doubly balanced type or better so that the dynamic range of this system can be expected large enough.

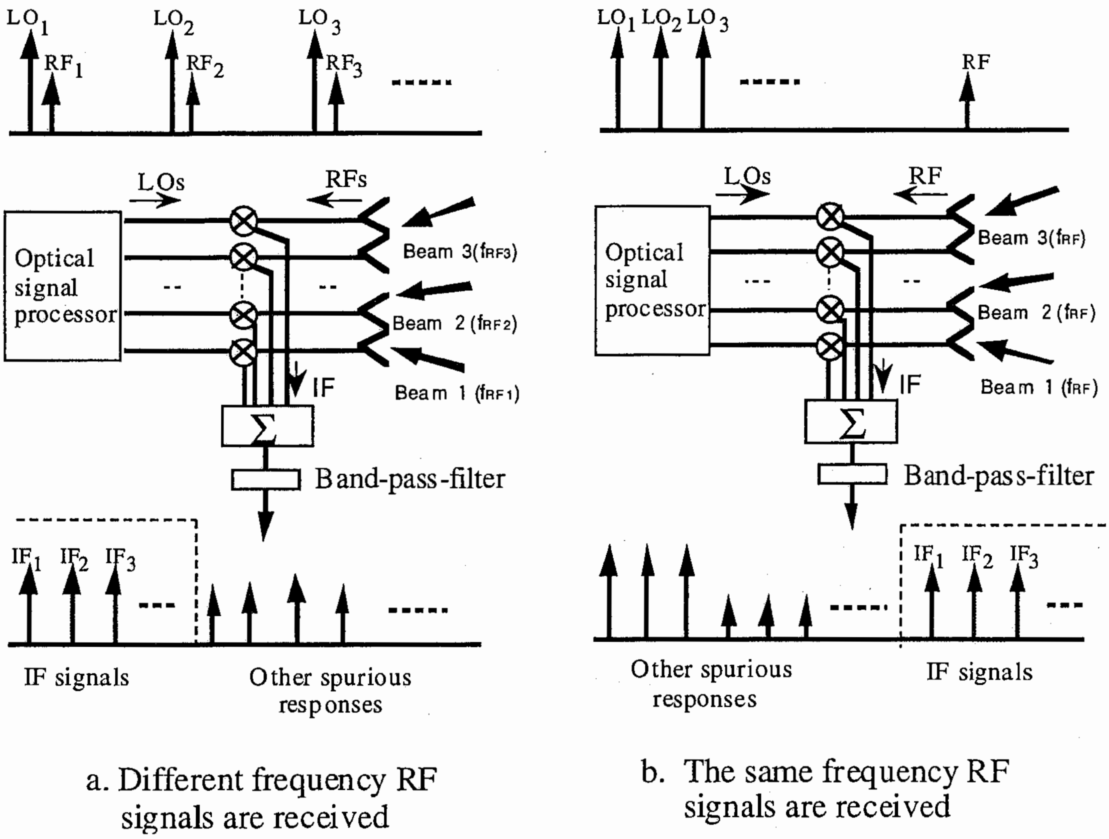

Fig. 2.2 Fequency arrangement in the receive mode

2.5. MULTIBEAM DISCRIMINATION IN THE IF FREQUENCY DOMAIN

When the mixer array inserts between optical processor and array antenna, the mixer works like a multiplier and phase detector. When sinusoid RF and LO signals apply to a mixer, the output is found to consist of two components at the sum and difference frequencies of RF and LO signals, as well as the sum and difference phase of these signals. The sum frequency is rejected by the IF filter, leaving only the lower IF frequency with phase difference. Therefore, the summed IF signals can be expressed as

$$S_{IFtotal} = \frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{N} A_n B_n \cos(\omega_{IFm} t + \Delta\phi_{mn}) \qquad (2.8)$$

An experimental setup for 2-beam and 4-element array as a support of the proposed receive mode is shown in Fig.2.3. As a proof-of-concept experiment, the different phase distribution of LO signals can be generated by a microwave hybrid junction instead of an optical processor. For a particular LO phase, by shifting the variable phase shifters, different phase gradients of RF signals which simulate the different arriving directions of RF signals can be made. After the downconversion and power-combination the IF power level distributions can be measured when the RF phase is varied. In a real receiving array antenna system, the received RF signal level is less than 1 mW (0 dBm) and the LO signal level is required to be more than 1 mW (0 dBm). In our experimental setup, the levels of RF and two LO signals were set as -10 dBm and 10 dBm, respectively, so that the high-order harmonics of the downconverted IF signals disappeared as low as the noise level.

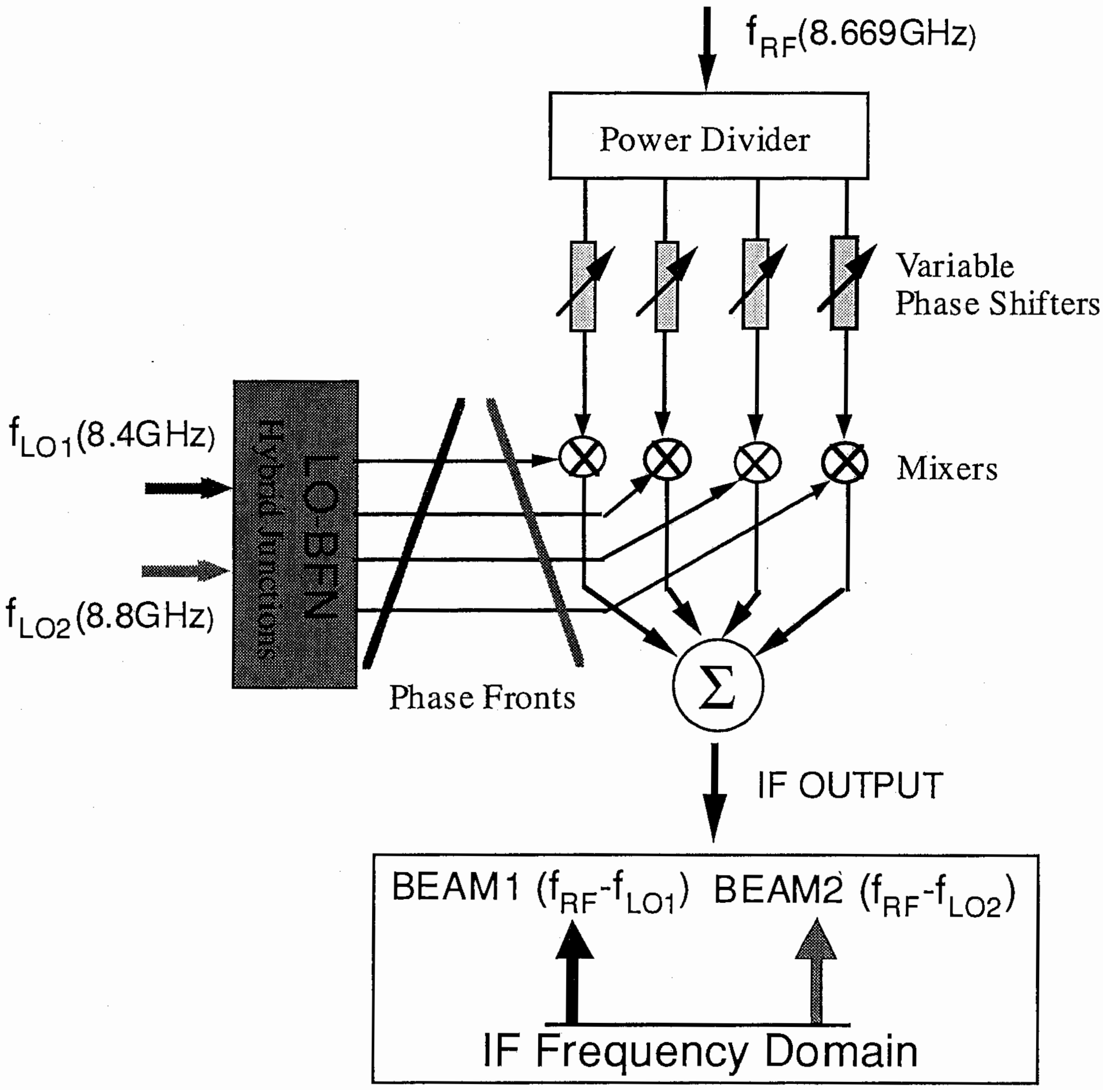

Fig. 2.3 Experimental setup

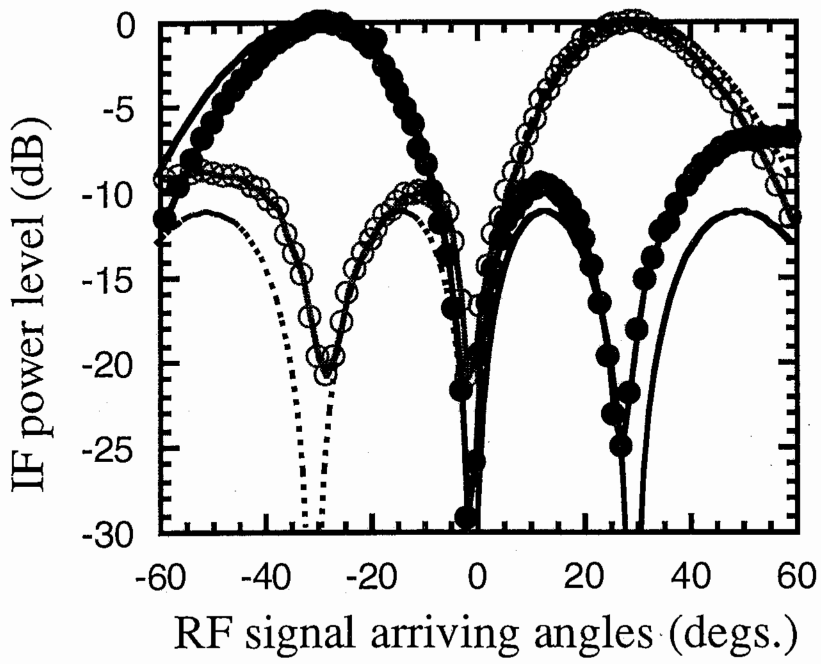

Fig. 2.4 Measured IF power level for multibeam reception

Fig.2.4 shows measured IF power distribution vs. the RF phase with a comparison of calculated antenna radiation patterns. When the RF phase is equal to the LO phase, the relative RF phase will be zero and the maximum IF power level will be obtained. Because of the reciprocity of antennas, good agreement between measurement and calculation is obtained in Fig. 2.4.

2.6. CONCLUSION

In this Chapter, we have described the receive mode of the optical processing multibeam array antennas. The basic concept and configuration of this receive mode have been presented. An experiment for two-beam reception in 4-element array has been demonstrated successfully. Based on the results shown in this paper, the receive mode will work as expected when an optical BFN is used to generate and process multiple beam signals.

Chapter 3

SUMMARY

In this technical report, I have described the concept of the optical signal processing multibeam array antennas, and the configuration of the transmit and receive mode of this type of antennas are given. The design method of the optical processor and its experimental performance have been presented as well.

As future works of optical signal processing array antennas, the following development problems are considerable.

(1) Reduction of the size and loss of the optical processor. Since the spatial optical processing of using Fourier Transform lens is the major technique of this antenna, the optical processor consists of 120cm-focal-length optical lens and optical stages at this moment, this makes the optical processor massive and inefficient of the power sampling. However, when slab optical waveguide and Rotaman lens design are used instead of the conventional optical lens, the optical processor will be expected to be miniature and functional.

(2) Beam squint problems. Beam squint means a undesirable shifting of the radiated beam led to a drop of the antenna gain in the main direction when the antenna is working at different frequencies. Although the broad band potential of the optical processing techniques has been recognized, when the broad band RF signals generated by an optical processor are used to feed the array antennas, the antennas actually can not radiate broad band beams, especially for large-size and high-gain array antennas. As demonstrated by many research groups, the true-time-delay (TTD) fiber techniques has the potential to solve this problem. However, TTD techniques are hardly to be employed to generated multiple beams. So the combination of the spatial optical processing and TTD techniques will be a promising approach in the future development.

(3) Common use of the optical processor for both transmit and receive mode. To commonly use an optical processor for both multibeam transmit and receive mode simultaneously, the frequency arrangement for RF and LO signals should be done carefully. Since mixer is a non-linear device, when multiple signals are inputted to a mixer, many unexpected spurious signals will be generated in the IF domain, which will influence the signal patterns of the received RF beams.

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