Receive Mode of Optical Signal Processing Multibeam Array Antennas

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***Abstract*— A receive mode of the optical processing array antennas is presented in this letter. In this receive mode, the transmitting radio frequency (RF) signals generated by optical processor will be shifted as local oscillator (LO) signals, and the received RF beams will be discriminated in the downconverted intermediate frequency (IF) frequency domain by a mixer array between optical processor and antenna elements. A proof-of-concept experiment for a two-beam and four-element array antenna is demonstrated, and the received IF power distributions for each beam have very good agreement with the calculated antenna patterns.**

***Index Terms*— Antenna arrays, optical signal processing, receiving antennas.**

I. Introduction

ARRAY antennas with a flexible beam-forming network (BFN) for the control of individual elements (radiators) are used widely in radar, satellite, and mobile communications as a most versatile type of antenna. 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 [2], [3], beam shaping [4], and multibeam operation [5].

However, so far there are only very few papers discussing the receive mode of the optical processing array antennas, especially for the multibeam operation [6], [7]. The reason is that the phase information of the received radio frequency (RF) multiple beams is difficult to maintain in the optical fibers which are the main parts in the optical BFN.

In this letter, 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 local oscillator (LO) signals, and the received RF beams will be discriminated in the downconverted intermediate frequency (IF) frequency domain by a mixer array between optical processor and antenna elements.

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II. Receive Operation of Optical Signal Processing Multibeam Array Antenna

In a receiving microwave antenna, usually, the 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 cannot be beamformers via a signal distribution network or BFN. Here, we describe 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 antennas. Therefore, a large number of variable phase distribution LO signals can be produced by the tunable lasers in the optical processor. Such a large number of LO signals are quite difficult to generate simultaneously by using RF techniques.

As shown in [5], 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. The mixers used here should be doubly balanced type or better so that the dynamic range of this system can be expected to be large enough. 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. 1, and the basic principle can be proved as in the following.

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

$$E_{Rmn} = Ae^{-j\omega_{Rm}t - jn\beta_m} \tag{1}$$

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

$$E_{Lmn} = Be^{-j\omega_{Lm}t - jn\alpha_m}. \tag{2}$$

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

$$E_{\mathrm{IF}mn} = ABe^{-j(\omega_{Rm}-\omega_{Lm})t - jn(\alpha_m - \beta_m)} \tag{3}$$

where

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

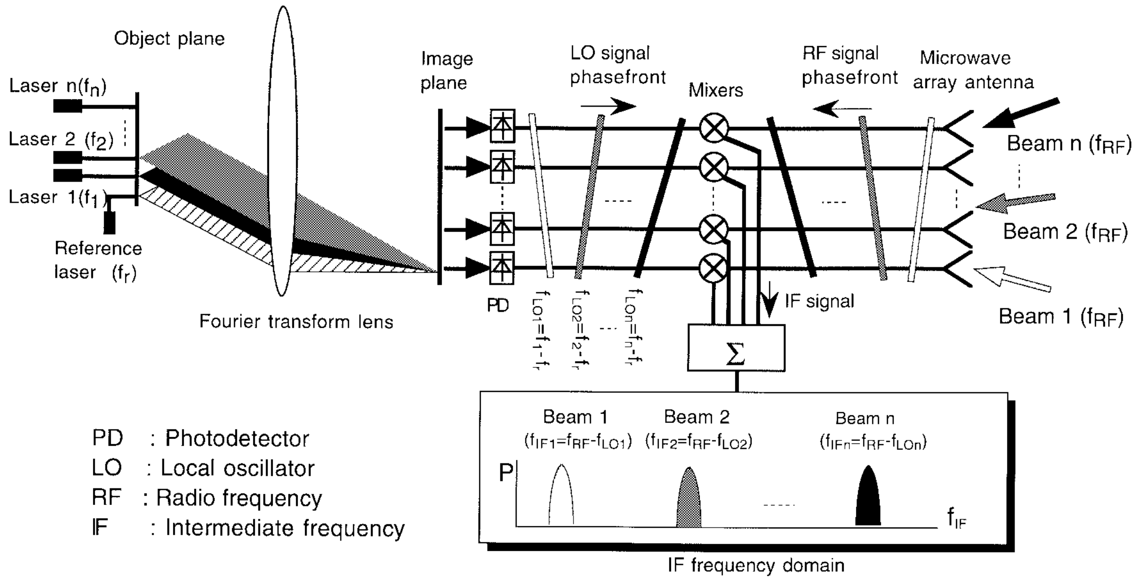

Fig. 1. Configuration of the receive mode.

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 (3) for beam m will be combined by an IF power combiner as

$$\begin{aligned} E_{\mathrm{IF}m} &= ABe^{-j\omega_{\mathrm{IF}m}t}\sum_{n}^{N-1} e^{jn(\alpha_m-\beta_m)} \\ &= ABe^{j\omega_{\mathrm{IF}m}t-j(N-1)\sigma_m/2}\frac{\sin N\sigma_m/2}{\sin\sigma_m/2} \end{aligned} \tag{4}$$

where $\omega_{\mathrm{IF}m} = \omega_{Lm} - \omega_{Rm}$ 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 (4) is N, when $\sigma_m = l \cdot 2\pi$, 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 an 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 should be in phase for a signal receiving at the array antenna from a particular direction, and will produce a maximum 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. 1, since the phase distributions of LO and RF signals have opposite gradients so as to obtain in-phase IF signals in the receive mode, the direction of received beams will become opposite to that of transmitting beams.

III. Multibeam Discrimination in the IF Frequency Domain

For multibeam receive operation of array antennas, the transmission lines between optical processor and 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. Although the spurious frequency responses can be filtered effectively by bandpass filters, the best way to avoid spurious responses is the careful frequency arrangement of RF, LO, and IF signals. 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

$$\begin{aligned} f_{\mathrm{IF}m} \leq |f_{\mathrm{LO}i} - f_{\mathrm{LO}j}|, |f_{\mathrm{RF}i} - f_{\mathrm{LO}j}|, |f_{\mathrm{RF}i} - f_{\mathrm{RF}j}|, \\ i, j = 0, 1, 2, \cdots,\ m, \cdots, M. \end{aligned} \tag{5}$$

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-bandpass filters. Otherwise, the spectrum groups of RF and LO signals should be separated enough compared to f_{IF}, and a bandpass 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

$$\begin{aligned} f_{\mathrm{IF}m} \geq |f_{\mathrm{LO}i} - f_{\mathrm{LO}j}|, 2|f_{\mathrm{LO}i} - f_{\mathrm{LO}j}|, \\ i, j = 1, 2, \cdots, m, \cdots, M. \end{aligned} \tag{6}$$

The expected IF signals will be the largest group in the downconverted frequency domain, and the unexpected spurious response will be rejected by low bandpass.

When the mixer array inserts between optical processor and array antenna, the mixer works like a multiplier and phase

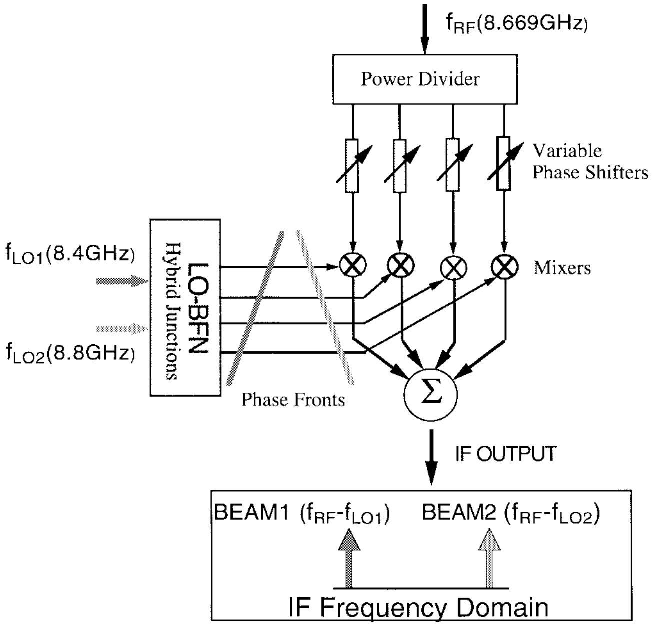

Fig. 2. Experimental setup.

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

$$S_{\mathrm{IFtotal}} = \frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{N} A_n B_n \cos(\omega_{\mathrm{IF}m} t + \Delta\phi_{mn}). \quad (7)$$

From the expression of single-beam radiation angle obtained in [7], the discrimination angle for multiple beams can be expressed as

$$\theta = M\frac{d_0}{F} \quad (8)$$

where

M beam magnification from optical domain to microwave domain;

d_0 distance between input fibers;

F focal length of optical processor.

An experimental setup for a two-beam and four-element array as a support of the proposed receive mode is shown in Fig. 2. Two 8.4- and 8.8-GHz signals as LO signals were input to a LO-BFN. One 8.669-GHz signal as a received RF signal was divided to four, and were downconverted by the mixers. 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

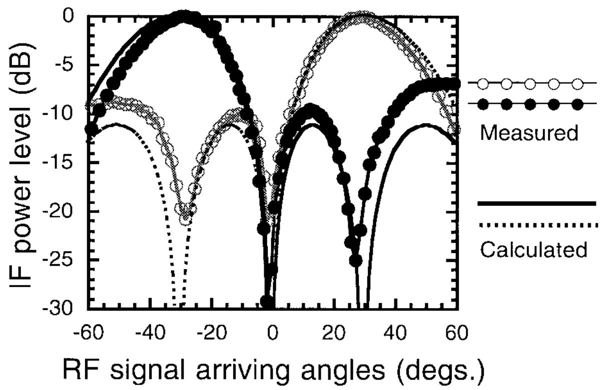

Fig. 3. Measured IF power level for multibeam reception.

distributions can be measured when the RF phase is varied. In our experimental setup, the levels of RF and two LO signals were set as −10 and 10 dBm, respectively, so that the high-order harmonics of the downconverted IF signals disappeared as low as the noise level. Further study of the potential limitation in LO power handling capability of mixers for multiple LO signal input is necessary.

Fig. 3 shows measured IF power distribution versus the RF signal arriving angles with a comparison of calculated antenna radiation patterns according to the reciprocity of antennas. When the phase gradient of the RF signal is equal to that of the LO signals, two points of the IF power level distribution for two different frequency IF signals are obtained.

IV. Conclusion

In this letter, 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 a four-element array has been demonstrated successfully. Based on the results shown in this letter, the receive mode will work as expected when an optical BFN is used to generate and process multiple beam signals.

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