

# Microwave Phase Conjugation Using Antenna Arrays

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**Abstract**— A technique has been developed and tested for achieving phase conjugation in the microwave and millimeter-wave regime. The effective nonlinearity required for this phase-conjugation process is provided by electronic mixing elements feeding an array of antennas. Using these balanced mixing circuits in conjunction with a one-dimensional array antenna, we have demonstrated two-dimensional free-space phase conjugation at 10.24 GHz. A critical factor of this technique is the delivery of a  $2\omega$  pump signal to each array element with the same phase. Two types of interconnects, electrical and a more versatile optical technique, have been implemented to distribute the pump signal in our demonstrations. In both systems, two-dimensional free-space phase conjugation was observed and verified by directly measuring the electric-field amplitude and phase distribution under various conditions. The electric-field wavefronts exhibited retro-directivity and the auto-correction characteristics of phase conjugation. Furthermore, these experiments have shown amplified conjugate-wave power up to ten times of that of the incoming wave. This amplifying ability demonstrates the potential of such arrays to be used in novel communications applications.

**Index Terms**—Antenna arrays, microwave, optical interconnection, phase conjugation.

## I. INTRODUCTION

THE engineering community has been interested in dynamically constructing desired wavefronts of electromagnetic (EM) waves for many years. Consequently, there has been a significant amount of theoretical and experimental work on this subject. The development of such techniques in the microwave and millimeter-wave regime has concentrated on phased-array antennas. The idea behind these phased arrays is fairly simple: by controlling the amplitudes and phases of discrete antenna elements, any wavefront can be dynamically generated or detected. In the past decade, researchers have been trying to realize compact phased-array systems with broad-band capabilities. The most promising concept calls for optically controlled designs because photonic components are small, light, broad-band, and relatively immune to EM interference. In this paper, special types of phased arrays, which incorporate phase-conjugate elements, have been developed and implemented. These phase-conjugation arrays can be thought of as automatically configured phased-array

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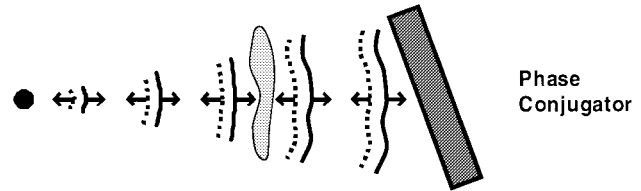


Fig. 1. Phase-conjugation properties: retro-directivity and automatic wavefront correction.

systems, which are capable of directing their outgoing signals back to the illuminating sources. We have demonstrated two-dimensional free-space phase conjugation at 10.24 GHz using both conventional microwave and novel photonic designs.

Phase conjugation, in general, utilizes the nonlinear susceptibility of a medium to reverse the phase factor of an incoming wave. A phase-conjugate wave propagates backward and has the same wavefronts as those of the incoming wave, as shown in Fig. 1 [1], [2]. This unique property of phase-conjugate waves is useful in many novel applications, including automatic pointing and tracking [3], phase aberration correction [4], and phase-conjugate resonators [5]. To further reveal phase-conjugation properties, let us consider an EM wave propagating along the positive  $z$ -direction. Its electric field can be written as

$$\mathbf{E} = \mathbf{A}(\mathbf{r})e^{i[\omega t - kz - \varphi(\mathbf{r})]} + \text{c.c.} \quad (1)$$

where  $\omega$  is the angular frequency and  $k$  is the wavenumber of the EM wave. The amplitude  $\mathbf{A}$  and the phase  $\varphi$  are real functions of position  $\mathbf{r}$ . Normally,  $\mathbf{A}$  is a slow-varying function of  $z$  compared with  $e^{i[\omega t - kz - \varphi(\mathbf{r})]}$ , therefore, the wave propagation can be understood in terms of the motion of wavefronts, which are three-dimensional surfaces defined by

$$kz + \varphi(\mathbf{r}) = \text{constant.} \quad (2)$$

The phase-conjugate wave of (1) is defined as

$$\mathbf{E}_C = \mathbf{A}(\mathbf{r})e^{i[\omega t + kz + \varphi(\mathbf{r})]} + \text{c.c.} \quad (3)$$

Comparing (1) and (3), it is shown that the two waves have the same wavefronts at any point in space, but they travel in opposite directions. Also notice that the conjugate wave can be obtained by a time-reversal  $t \rightarrow -t$  transformation or by taking the complex conjugate only of the spatial part of the electric field.

To appreciate the properties of phase conjugation, let us consider a plane wave propagating through a distorting medium. Due to the nonuniform distribution of refractive

index  $n(\mathbf{r})$ , the incident wavefronts are no longer planar after passing through the distorting medium. Equations (1) and (3) have shown that the conjugate wave has the same wavefronts as those of the incident wave. It can be proven the phase-conjugate wave satisfies Maxwell's equations, therefore, it propagates backward as the time-reversed incident wave through both space and the distorting medium and, consequently, the distortion is automatically removed [2]. Another important feature of phase conjugation is that we only need to generate the conjugate field  $\mathbf{E}_c$  on one plane, this field will propagate backward and remain the phase-conjugate field of  $\mathbf{E}$  everywhere [2]. This enables the possibility of accomplishing microwave and millimeter-wave phase conjugation using electronic-mixing phased-array antennas system.

To date, most of the phase-conjugation development has been concentrated in the optical [visible and infrared (IR)] regime. Efforts to extend this technique to microwave and millimeter-wave frequencies have encountered severe difficulties due to the small nonlinearity of natural materials and the low-power density of sources at these frequencies. To examine this problem, let us consider the phase-conjugation efficiency of degenerate four-wave mixing (DFWM) [2] techniques. Applying nominal parameters, this efficiency is lowered by about 16 orders of magnitude as one tries to extend optical DFWM techniques into microwave and millimeter-wave regime [6]. This drastic efficiency loss presents severe difficulties for microwave and millimeter-wave phase conjugation.

One possible solution for the above-mentioned efficiency problem is to increase the nonlinear susceptibility by many orders of magnitude. In the search for alternative nonlinear substances suitable for the use in microwave and millimeter-wave phase conjugation, artificial Kerr media were found to have much larger nonlinearity than that of natural materials. Using shaped microparticle suspensions [7] and microelectromechanical system (MEMS) structures [8], [9], volume grating formation for microwave phase conjugation has been demonstrated with DFWM techniques. Although these artificial Kerr media have demonstrated  $\chi^{(3)}$  as high as  $10^{-4} \text{ cm} \cdot \text{s}^2/\text{g}$  [6], they have a number of intrinsic problems. Due to the required movements of macroscopic particles in viscous fluid or polyimide supported metal beams in air, these media suffer from slow response time and are sensitive to surrounding conditions. Therefore, these techniques are not suitable for practical systems and applications.

## II. ANTENNA-ARRAY APPROACH

Due to the above-mentioned difficulties in achieving microwave phase conjugation using traditional DFWM techniques, this paper approaches the problem from a very different perspective. Instead of using third-order nonlinear dipoles ( $\chi^{(3)}$ ), as in DFWM, electronic-mixing phased arrays are used in a second-order three-wave mixing configuration to provide a high artificial nonlinearity for generating phase-conjugate waves. In this approach, microwave circuits, which combine antennas and mixers, effectively replace the roles of nonlinear dipoles of a medium. The idea is to "sample" the incident

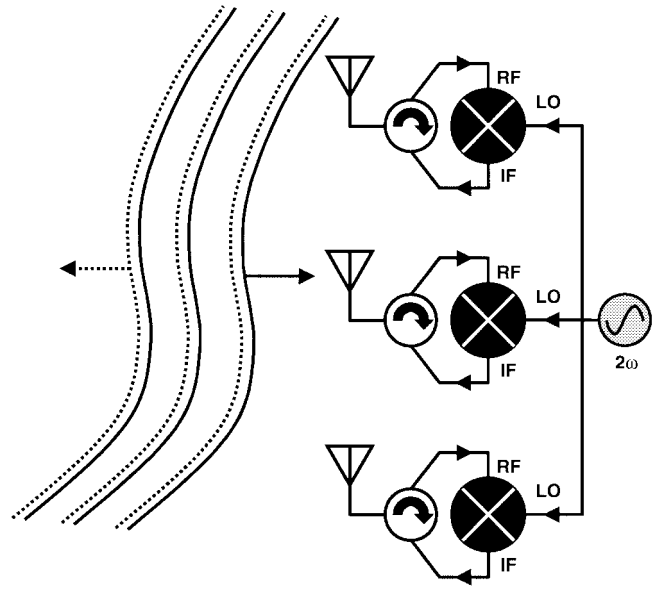


Fig. 2. First, the incident wavefront is sampled at different positions. Each element then generates a phase-conjugate current using microwave circuitry. This current will excite a phase-conjugate field at the sampling point. The superposition of these fields becomes the phase-conjugate wave.

wave at different positions of the wavefront using antenna elements and then generate phase-conjugate currents using microwave mixers. These currents will then excite a phase-conjugate field at each sampling point. The combined field of all the elements will be the phase-conjugate field of the incident beam. This sample-then-mix concept is shown in Fig. 2. It was first proposed in the 1960's, but due to the lack of modern semiconductor and photonic technologies, researchers did not have practical ways to realize this concept [10], [11].

To understand how the conjugate signal can be generated at each element using microwave circuitry, let us consider again the incident wave shown in (1). At the  $j$ th element of the array, the incoming electric field is

$$\mathbf{E} = \mathbf{A}(\mathbf{r}_j)e^{i(\omega t - \varphi_j)} + \text{c.c.} \quad (4)$$

where

$$\varphi_j = kz_j + \varphi(\mathbf{r}_j). \quad (5)$$

The signal picked up by the antenna and then sent to the mixer can be written as

$$V_{j1} \propto A(r_j)e^{i(\omega t - \varphi_j)} + \text{c.c.} \quad (6)$$

Now consider a  $2\omega$  signal delivered to the local oscillator (LO) port of the mixer given by

$$V_{j2} = Ce^{2i\omega t} + \text{c.c.} \quad (7)$$

This  $2\omega$  pump signal has to be delivered to all elements at the same amplitude and phase; otherwise, the mixed output will contain a term other than  $V_{jt}$  that depends on  $j$ . If this ever happens, the sum of the excited field at each element will be distorted and will not form the conjugate beam. Now, through different frequency generation in the mixer, the intermediate frequency (IF) output contains a current component

$$I_C \propto e^{2i\omega t} \times e^{-i(\omega t - \varphi_j)} = e^{i(\omega t + \varphi_j)}. \quad (8)$$

This current component has the conjugate-phase  $+\varphi_j$  instead of the input phase  $-\varphi_j$ , therefore, it will excite the conjugate field at  $\mathbf{r}_j$  when delivered to the antenna

$$\mathbf{E}_{C_j}(\mathbf{r}_j) \propto \mathbf{A}(\mathbf{r}_j)e^{i(\omega t + \varphi_j)} + \text{c.c.} \quad (9)$$

When the sampling spacing is less than  $\lambda/2$ , the combined field  $\mathbf{E}_c(\mathbf{r}) = \sum_j \mathbf{E}_{C_j}(\mathbf{r})$  forms the phase-conjugate signal on the sampling surface. It has been discussed earlier that if a phase-conjugate field is generated on a plane, it will propagate backward and be conjugate to the incident beam everywhere. Therefore,  $\mathbf{E}_c(\mathbf{r})$  is the desired phase-conjugate field. In the past three years, various groups have explored retro-directive phased arrays utilizing this concept [12], [13]. These studies have concentrated on the retro-directive property of phase conjugation. In this paper, we focus on wavefront properties and reconstruction, and also investigate optical interconnection for the  $2\omega$  pump signal so that large phase-conjugation arrays can be constructed with less complexity.

There is an important issue we have to address here. Unlike any of the traditional phase-conjugation techniques, which utilize virtually infinite dipoles as far as our concern, this array approach can only have a limited number of elements because of economic and engineering constraints. To clarify the effects caused by a finite number of elements, the phase-conjugate wave of a dipole source has been calculated for three phase-conjugate arrays having different number of elements. The first array was formed by eight elements, the second one by 40 elements, and the third one by 200 elements. For the eight- and 40-element arrays, the spacing between elements was chosen to be  $0.467\lambda$ . The 200-element array had a spacing of  $0.093\lambda$ , which was one-fifth of that of the 40-element array. Therefore, the 40-element array had five times the aperture size of the eight-element one, with the same sampling density. The 200-element array had the same aperture size as the 40-element one, but with five times the sampling density. The antenna elements were assumed to have dipole radiation patterns and collinear axes.

In the calculation, the center of each array was used as the origin. The wavelength was assumed to be 3 cm, which corresponds to 10 GHz in frequency. Fig. 3 shows the conjugate electric-field magnitude distribution generated by the eight-element array at a given time. It clearly exhibits retro-directivity, but does not show the conjugate beam focusing back to the source. This is caused by the diffraction effects of a small aperture size. The conjugate electric-field distribution of the 40-element array is shown in Fig. 4. It demonstrates fairly well wavefront reconstruction, as well as retro-directivity and focusing can be clearly seen. The calculated conjugate field distribution of the 200-element array displays no perceivable improvement over the 40-element one. Therefore, a sampling spacing slightly less than  $\lambda/2$  is acceptable for most cases. If the spacing is greater than  $\lambda/2$ , grating sidelobes can develop and, therefore, destroy the conjugate wavefront patterns.

From these comparisons, we have seen the main factor determining that the resolution is not the sampling density (as long as it is greater than  $2/\lambda$ ), but the aperture size. If we require the phase conjugator to have a high resolving power, equally spaced arrays with  $< \lambda/2$  spacing, like the examples,

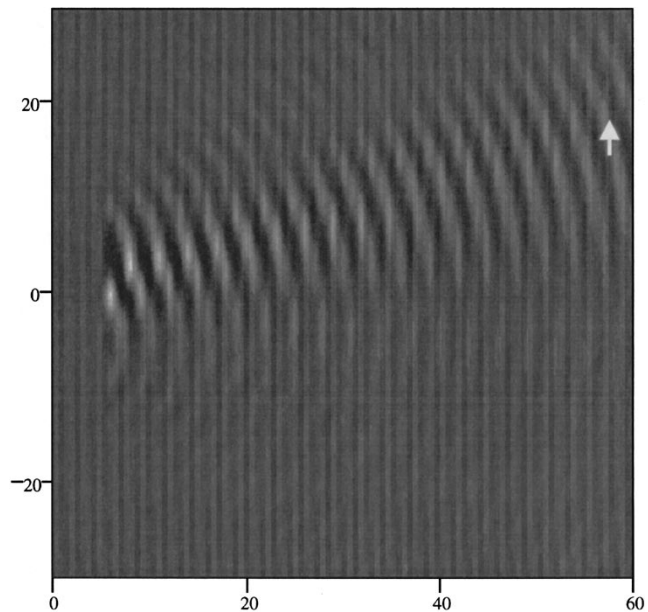


Fig. 3. The calculated conjugate electric-field magnitude distribution generated by an eight-element array. Brighter areas represent higher field. The element spacing is  $0.467\lambda$  and a dipole source is located at (57.9 cm, 15.6 cm), as marked by the arrow. Only retro-directivity is observable in this configuration because of diffraction effects.

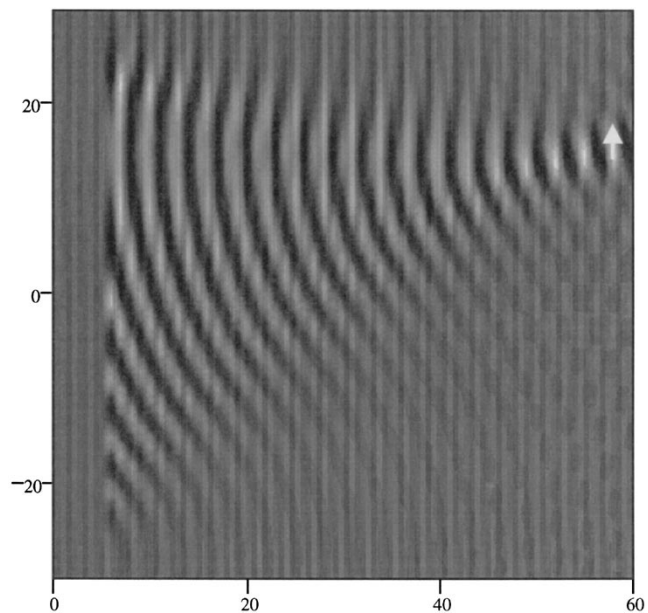


Fig. 4. The calculated conjugate electric-field magnitude distribution generated by a 40-element array. The element spacing is  $0.467\lambda$ . Both retro-directivity and focusing can be clearly observed at this aperture size.

will not be practical, as the number of elements will be astronomical. For example, a resolving power of  $10^{-5}$ – $10^{-4}$  rad could require  $4 \times 10^8$  to  $4 \times 10^{10}$  elements. However, using randomly distributed elements over the aperture to prevent the development of grating lobes can dramatically reduce the number of elements required in a sparse array [14].

### III. ELECTRICAL-INTERCONNECTION EXPERIMENTS

The concepts of microwave phase conjugation using electronic-mixing antenna arrays have been discussed in

Section II. To prove the feasibility of this approach, we have built an array of eight phase-conjugate elements to demonstrate the generation of phase-conjugate waves. The equipment and devices available to us limited the number of elements used in this demonstration. Although an eight-element array would not be able to focus a diverging incident beam back to its source due to diffraction limitations (as calculated in Section II), it should exhibit retro-directivity and can demonstrate phase autocorrection when a distortion medium is introduced into the beam path. These two key characteristics of phase conjugation are strong evidences of the feasibility of this technique.

Since microwave components have relatively large loss, size, and weight, and are more susceptible to EM interference, we find that optical interconnection is the crucial technology for constructing large microwave phase-conjugate arrays. However, for an eight-element demonstration array, it is still feasible to build a system using straightforward microwave interconnects. Therefore, in this section, we will first discuss the construction and measurements of an electrically interconnected phase-conjugate array. Its optically interconnected counterpart will be considered in Section IV.

As mentioned in Section II, each element of a phase-conjugate array will excite the conjugate field at its sampling position via difference frequency generation. In an ideal elementary configuration, the sampled signal goes through a circulator into a low-noise amplifier. This amplifier provides compensation to the conversion loss of the mixing process in the next step. It can also provide gain so that the conjugate signal is more intense than the input one. After mixing with the  $2\omega$  pump signal in a mixer, the output IF signal has the conjugate phase and it is sent back to the sampling antenna through the circulator. In this configuration, the antenna has to be very efficient. The reason is that any reflection of the conjugate signal from the antenna will go through the circulator, as it were the sampled incident signal. This will affect the phase of the output signal and, thus, destroy the conjugate-phase generation. If the reflection is large enough, the circuit will even start oscillating by itself. To study this more closely, let us assume the return loss of the antenna is  $R$ , gain of the amplifier is  $G$  and conversion loss of the mixer is  $C$ .  $R$ ,  $G$ , and  $C$  are complex output to input voltage ratios to include the phase change at each stage. The circulator and mixer are assumed to be perfect, no unwanted signal leakage between their ports. In order to generate the phase-conjugate wave, we require that the reflected conjugate signal be much smaller than the sampled signal. This requirement can be written as

$$G \cdot C \cdot R \ll 1 \tag{10}$$

and when  $G \cdot C \cdot R = 1$ , the system starts to oscillate.

Commercial mixers normally have a conversion loss around 10 dB, which corresponds to  $|C| = 0.32$ . With a specially designed narrow-band antenna array, a 30-dB return loss can be achieved. This corresponds to  $|R| = 0.032$ . Equation (10) gives us  $|G| \ll 100$ . If we choose  $|G| = 10$ , the phase-conjugate signal will be ten times more powerful than the incident signal. Unfortunately, the antenna array available to us had a return loss of about 7 dB at the desired

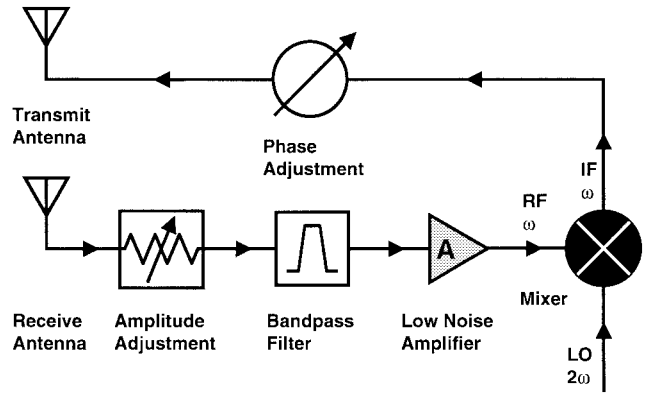


Fig. 5. The configuration of a phase-conjugate element used in this paper. The transmit and receive antennas are separated. A bandpass filter, phase adjustment, and amplitude adjustment are added to the circuit.

10.24 GHz, which corresponded to  $|R| = 0.45$ . This high reflection was a direct consequence of the wide-band design of the antenna array. Applying (10), we obtained  $|G| \ll 7$ . Basically, this means there could be no gain in this phase-conjugate element. Therefore, we somehow needed to reduce the antenna reflection.

Since we planned to demonstrate a two-dimensional free-space phase conjugation using a one-dimensional electronic-mixing antenna array, instead of designing new antennas, we had chosen to separate the transmit and receive antennas. This means the sampling of the incident field and the excitation of the conjugate field happened at the same  $(x, y)$  coordinates, but at a slightly different vertical  $z$ -coordinate. This small shift in the  $z$ -direction would only disturb the electric-field distribution on the  $z = 0$  plane to a negligible level.

The modified elementary configuration used in this paper is shown in Fig. 5. An amplitude adjustment and a phase adjustment had been added to the configuration to compensate for any differences between the phase-conjugate elements because the amplifiers and mixers were not matched. By displaying and comparing the output signal of each element to a reference signal using a computer-controlled digital sampling oscilloscope (DSO), the phase and amplitude of each element could be measured and adjusted. The amplitudes of all phase-conjugate elements were first matched with different attenuators to within  $\pm 2\%$ . The phases were then matched to within  $\pm 0.2$  ps (0.2%) by adjusting the variable delay line of each element.

The mixer is the key component of the phase-conjugate element. It provides the nonlinearity for generating phase-conjugate waves. In this study, MY50C triple-balanced mixers from Watkins-Johnson were used. The conversion loss of these mixers at 10.24-GHz input and output signals with a 20.48-GHz pump (LO) signal is around 10 dB. The leakage from the input (RF) to the output port (IF) of the mixer is about  $-20$  dB. Therefore, the unwanted 10.24-GHz input leakage is 10 dB smaller than the desired phase-conjugate output signal. This can be further reduced by designing mixers for the desired frequency or by using a two-stage mixing technique. In a two-stage mixing element, the undesired incoming frequency can be filtered out by a bandpass filter after the first-stage mixing.

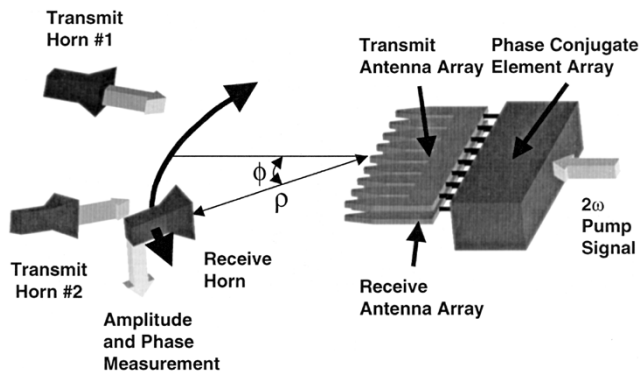


Fig. 6. This setup is used to map out two-dimensional electric-field magnitude distribution. The receive horn is at a lower height than the transmit horns to prevent blocking of the incident beams. It can be moved to different positions to measure the electric-field strength.

This filtered signal can then be mixed in the second stage to produce the final conjugate signal. Again, a second bandpass filter can filter out any undesired leakage signals. This four-wave mixing technique can achieve higher isolation between the incoming signal and the conjugate signal at the cost of an additional pump source for each element. The details of this technique will be explained later.

To demonstrate microwave phase conjugation using the eight-element electronic mixing array, we prepared an electric-field mapping setup in an anechoic chamber, shown in Fig. 6. As mentioned earlier, the transmit and receive antennas of the conjugator were separated in the  $z$ -direction (height) by 1.4 cm. One or two transmit horns were used as illuminating sources. Both transmit horns were 60 cm from the conjugator. This distance was chosen because of the sizes of the chamber and conjugator. The receive horn was mounted on a translation stage for radial movement. Its distance to the conjugator ( $\rho$ ) was varied at 0.5 cm intervals from  $\rho = 45$  cm to  $\rho = 55$  cm. The translation stage itself was mounted on a stepping motor stage for angular control. A computer controlled the rotation stage at  $1^\circ$  intervals from  $\phi = -30^\circ$  to  $\phi = 30^\circ$ . The signal detected by the receive horn was proportional to the electric field at that point and was amplified and then displayed on a DSO. By comparing the received signal to a reference signal using a computer, the amplitude and phase of the electric field at the receiving horn position could be accurately measured.

In the first set of measurements, only one transmit horn was used as the source. It was placed at  $\phi = 15^\circ$ . This angle was chosen for convenience, it could be varied between  $-30^\circ$  to  $30^\circ$ . The conjugate electric-field distribution is shown in Figs. 7 and 8, labeled as "without distortion." In the contour plot of Fig. 7, gray scale is used to represent the magnitude of the electric field. The black dot next to the plot is the source location. The phase-conjugate array is located on the left of each plot and the tick mark labels are in centimeters. The wavefronts of the conjugate wave can be seen clearly, and are traveling from left to right. Although the focusing effect cannot be observed because of the diffraction limits, retro-directivity is certainly demonstrated. In the surface plot of Fig. 8, the electric-field magnitude is represented by the height at a given

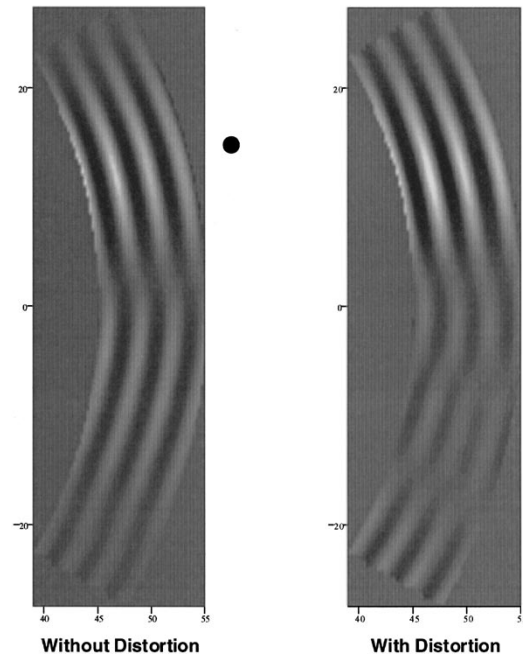


Fig. 7. The contour plots of the measured phase-conjugate electric field of a source at  $+15^\circ$ , as marked by the black dots. The high-contrast areas represent the conjugate beams, and the faint fringes are due to leakage. They demonstrate retro-directivity and automatic phase correction when a distorting medium is inserted in front of the conjugator.

point. The white dot on the zeroth-field plane marks the source position. The smaller bumps in this figure were caused mainly by the amplified incident signals leaking through the mixers. This amplitude of the electric field was about one-third to one-fourth of that of the conjugate beam. This means the leakage power was about  $-10$  dB of the conjugate power, as mentioned earlier in this section.

Our next step was to demonstrate automatic phase correction. This was achieved by inserting a distorting medium in front of the phase conjugator. We used a piece of Plexiglas as the distorting medium. The conjugate electric field is shown in Figs. 7 and 8, labeled as "with distortion." By comparing the fringes of the two plots in Fig. 7, the wavefronts of the conjugate beam remained the same shape and phase with or without the distortion, as the theory predicted. The leakage wavefronts were distorted when the distorting medium was present. In Fig. 8, the leakage bumps were again destroyed by the distortion, while the phase-conjugate beam maintained its phase and amplitude. These results unambiguously demonstrate the retro-directivity and automatic phase correction ability of this microwave phase conjugation.

In order to reveal the automatic phase correction more quantitatively, the receive horn was placed in the conjugate beam at 55 cm from the conjugator. The electric field versus time was recorded and then compared with and without the distortion. The phase difference in time was less than 1 ps for a distorting medium capable of 25-ps one-way delay. To further demonstrate that the phase-conjugate beam does carry a negative incident phase, we moved the distorting medium to cover the source only. Therefore, only the incident beam went through the distortion. The electric-field distribution is

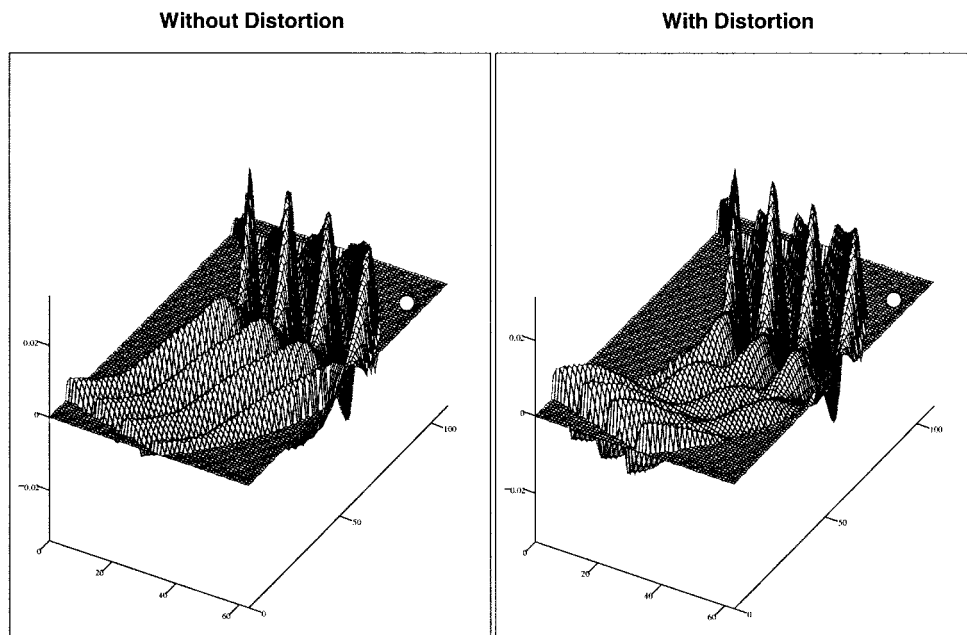


Fig. 8. The surface plots of the phase-conjugate electric field of a source at  $+15^\circ$ , as marked by the white dots. They show retro-directivity and automatic phase correction. The smaller bumps are caused by amplified leakage and are destroyed by the distortion.

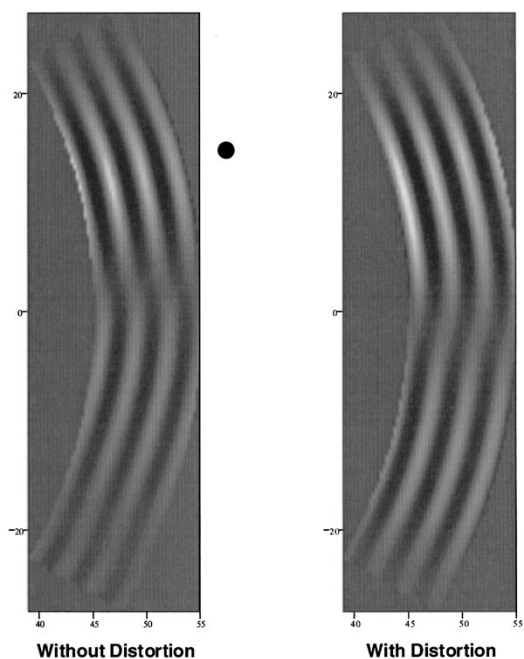


Fig. 9. This data is taken with the distorting medium covering only the transmit horn. The conjugate beam now has advanced wavefronts, while the reflected beam is distorted and has retarded wavefronts.

shown in Fig. 9, labeled as “with distortion.” Due to the existence of the distorting medium, the phase of the incident beam was retarded by  $\Delta\varphi$ . If this signal was leakage, it would carry the same phase retardation  $\Delta\varphi$ . However, if the incident beam was phase-conjugated by the conjugator, the phase of the conjugate beam would be  $-\Delta\varphi$ , which means its phase was advanced by  $\Delta\varphi$ . This theory is shown in Fig. 9 as the conjugate wavefronts moved toward the source (advanced phase), while the leakage wavefronts moved

toward the conjugator (retarded phase). Also noticeable in Fig. 9, the leakage beam was deflected away from the center because of the distortion. This shows the Plexiglas did act as an effective distorting material and further confirms the previous experiments.

#### IV. OPTICAL-INTERCONNECTION EXPERIMENTS

As mentioned earlier, electrical interconnection will not be able to handle a large two-dimensional phase-conjugate array for complete three-dimensional wavefront reconstruction. The problems in the electrical scheme are due to the high loss, heavy weight, and large size of microwave and millimeter-wave components. It is also more susceptible to EM interference. In contrast, using optical interconnection, the  $2\omega$  pump signal can be delivered to all elements with very little loss ( $\sim 0.3$  dB/Km) at very high density (e.g., 1 element/millimeter for millimeter-wave arrays). Therefore, in this paper, we propose and demonstrate the optical-interconnection technique to address these electrical-interconnection problems.

In this optical-interconnection scheme, the eight phase-conjugate elements were the same as in the electrical configuration shown in Fig. 5. A Lightwave 122 diode-pumped Nd:YAG laser was used as the light source. The optical wavelength was at 1319 nm, with a linewidth  $\leq 5$  KHz. This wavelength was chosen to minimize the dispersion in optical fiber systems. In our demonstration, it was not an important issue because of the relatively short propagation distances. However, to be able to extend this technique into large arrays and/or millimeter-wave frequencies, minimized dispersion will be a crucial factor.

The laser light was directed into a Mach-Zehnder optical modulator using a polarization preservation fiber. The modulator was biased at its transfer function halfway point for optimal linear modulation. The 10.24-GHz signal was

frequency-doubled to 20.48 GHz, amplified, and then used to modulate the laser light. A more interesting way to modulate the light at  $2\omega$  is to bias the modulator at its transfer function minimum and apply an  $\omega$  signal to its RF electrode. Due to the nonlinearity of the transfer function at the minimum, the optical power varies at  $2\omega$  as desired. The advantage of this technique is that no microwave frequency-doubler is required. The disadvantage is that it is very sensitive to the bias of the transfer function. Even small fluctuations will result in loss of modulation efficiency and unwanted linear modulation. Therefore, the bias point has to be monitored closely by a feedback loop.

This  $2\omega$  modulated light can now be delivered to photodetector-attached phase-conjugate elements, which may be far away for a large array or close together for high operating frequencies. In this paper, this 20.48-GHz modulated light entered an  $1 \times 8$  optical power splitter and split into eight equal-intensity equal-phase signals. The 20.48-GHz pump signal was then extracted by a p-i-n diode at each element. This pump signal was amplified to a power level of 9 dBm, and then fed to the phase-conjugate element, as in the electrically interconnected system.

Using the experimental setups and procedures mentioned earlier, the output amplitudes of these eight elements were matched to within  $\pm 6\%$  and their phases were matched to within  $\pm 0.2$  ps (0.2%). After this calibration, we were able to demonstrate two-dimensional microwave phase conjugation using the optically interconnected electronic-mixing array. All the tests performed in the electrical demonstration have been successfully duplicated.

To demonstrate phase conjugation with more complicated wavefronts, we used two sources located at  $15^\circ$  and  $-20^\circ$ , both were 60 cm from the conjugator. Due to the interference between the two sources, the combined incident wavefronts represented a good example of complicated wavefronts. The results are shown in Fig. 10, labeled as "without distortion." They exhibit multiple-source retro-directivity with both conjugate beams shifted  $\sim 3^\circ$  toward the negative angles. This was caused by the interference between the leakage of one source and the conjugate beam of the other. To prove this point, the following test was performed. First, the horn at  $-20^\circ$  was disconnected from the source and the conjugate field of the  $+15^\circ$  horn was recorded. Then the horn at  $+15^\circ$  was disconnected and the field of  $-20^\circ$  was measured. In both cases, retro-directivity was shown without the angular shift. A computer then added up the two single-source electric fields. The calculated sum field showed the same angular shift and was almost identical to the measured two-source electric field. Therefore, the interference from the leakages was causing this problem and can be solved by using two-stage mixing to avoid leakage. In order to verify the phase-correction ability, a distorting medium was inserted in front of the conjugator. The conjugate electric-field distribution is shown in Fig. 10, labeled as "with distortion." By comparing the two plots in Fig. 10, the automatic phase-correction effect can be confirmed. It can also be noticed that the small angular shift disappeared when the distortion was present. This is because the existence of the distorting medium destroyed the leakage

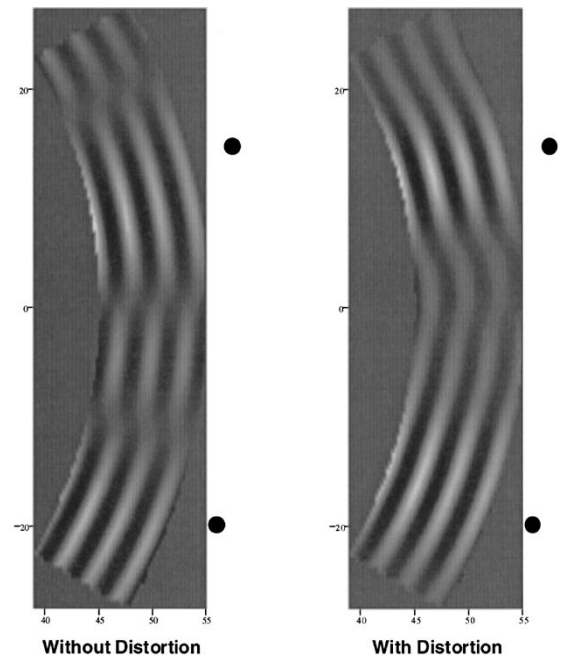


Fig. 10. The phase-conjugate electric-field distribution of two sources at  $+15^\circ$  and  $-20^\circ$ , obtained using an optically interconnected phase-conjugate array. These plots demonstrate multiple-source retro-directivity and automatic phase correction when a distorting medium is inserted in front of the conjugator.

signal while maintaining the conjugate signal, as shown in previous experiments.

To test that a phase conjugator can transmit information back to the source, we A.M. modulated the 20.48-GHz pump signal before it was used to modulate the light. In this example, the modulation frequency was set to 10 MHz. This frequency was chosen by convenience and can be varied as long as it is small compared to the phase-conjugation frequency. If it becomes comparable to the phase-conjugation frequency, the output signal will not be the conjugate beam any more. The two sources used in the previous experiments were used to illuminate the conjugator. The detected spectra at different angles are shown in Fig. 11. The top spectrum was detected in the  $+15^\circ$  conjugate beam. It shows the 10.24-GHz carrier and two A.M. modulation sidebands at 10.23 and 10.25 GHz. The bottom spectrum was detected in the  $-20^\circ$  conjugate beam and it shows the same characteristics as the  $+15^\circ$  one. When the receive horn was moved out of the conjugate beams to  $0^\circ$ , the carrier and sidebands were about 20 dB lower than those of the conjugate beams. The signal detected here was mainly due to diffraction and leakage. Using a large phase-conjugate array and two-stage mixing, this contrast ratio can be further increased because of the reduction of diffraction effects and mixer leakage.

## V. CONCLUSIONS

Thus far, we have demonstrated two-dimensional microwave phase conjugation in free space. In order to extend this effort to complete three-dimensional wavefront reconstruction, two-dimensional arrays will have to be used. At microwave frequencies, a phase-conjugate array can be

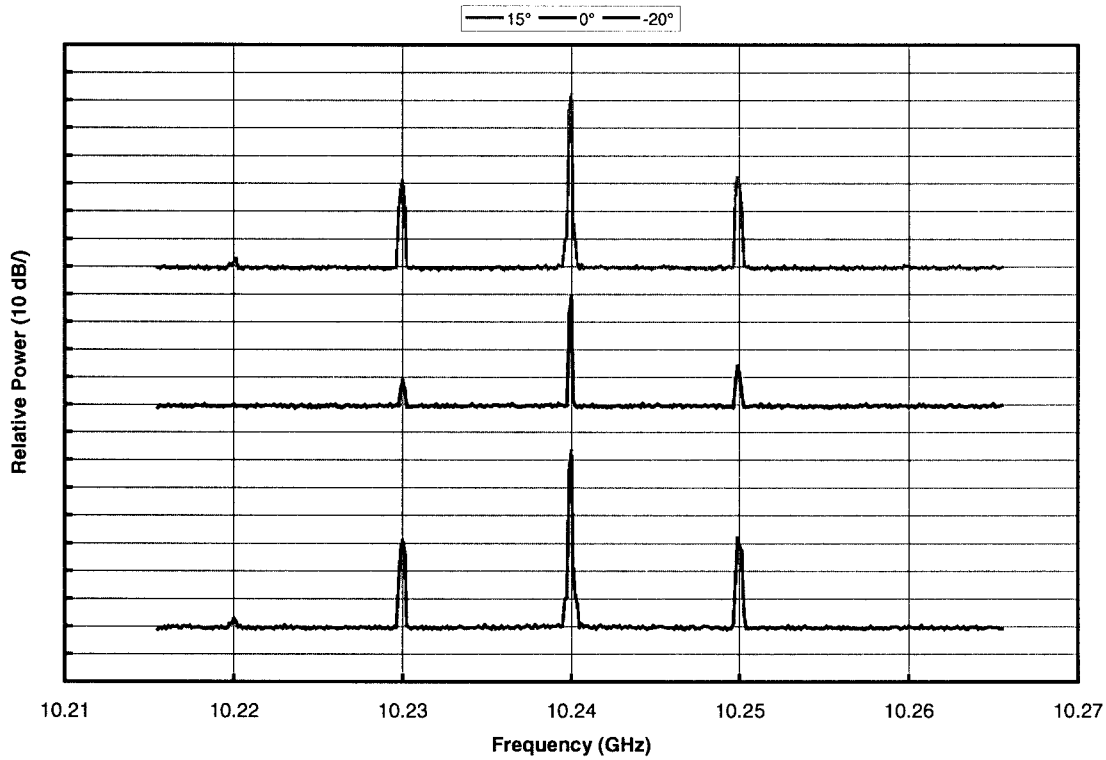


Fig. 11. Detected spectra at different angles with a modulation on the pump signal. This demonstrates that retro-directivity can also be used to communicate between a conjugator and its illuminating sources. The top curve and bottom curve represent the two conjugate beams. The leakage signal between the conjugate beams is about 20 dB smaller than the conjugate beams. These spectra have been moved in the vertical direction for easier comparison.

constructed using discrete components, as done in this paper. As we have demonstrated, optical interconnections can solve the  $2\omega$  pump signal distribution problem for large two-dimensional arrays. However, in the millimeter-wave regime, monolithic design will be needed in order to satisfy the small  $\lambda/2$  spacing requirement. Using high-speed photodetectors and mixing devices [15], [16] in conjunction with on-wafer polyimide optical waveguides [17], two-dimensional millimeter-wave phase-conjugate surfaces can be realized. Fig. 12 shows this concept.

To address the problem of amplified leakage signals coming out from our phase-conjugate elements, a two-stage mixing technique has been proposed [11]. To understand how it works, let us consider that the sampled incident signal has a phase factor of  $\omega t - \varphi$ . This incident signal will be mixed with a pump signal having a phase factor of  $\Omega t$ , where  $\omega < \Omega < 2\omega$  and this phase factor  $\Omega t$  is the same for all elements. After the first-stage mixing, there will be four major components coming out from the mixer:  $(\Omega - \omega)t + \varphi$ ,  $(\Omega + \omega)t - \varphi$ ,  $\omega t - \varphi$ , and  $\Omega t$ . The first term is the signal we want because of its reversed phase  $+\varphi$ . The second term is the sum frequency, and the last two terms are the leakage through the mixer. Since these four signals are at different frequencies if  $\Omega \neq 2\omega$ , a bandpass filter at  $\Omega - \omega$  can be used to remove the three unwanted components. A second-stage mixing is needed because the signal carrying the conjugate phase is not yet at the incident frequency. To convert the  $(\Omega - \omega)t + \varphi$  signal back to frequency  $\omega$ , it is mixed with a second pump signal  $(2\omega - \Omega)t$ . Again, this pump signal has to be the same for all elements. As in

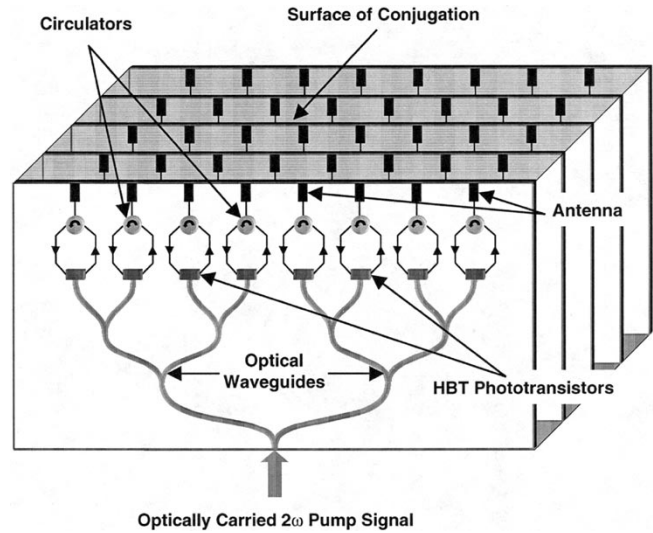


Fig. 12. Monolithic one-dimensional arrays forming a two-dimensional artificial nonlinear surface for generating three-dimensional microwave phase conjugation.

the first stage, four components will appear on the output port:  $\omega t + \varphi$ ,  $(2\Omega - 3\omega)t + \varphi$  or  $(3\omega - 2\Omega)t - \varphi$ ,  $(\Omega - \omega)t + \varphi$ , and  $(2\omega - \Omega)t$ . Using a second bandpass filter at frequency  $\omega$ , only the conjugate signal  $\omega t + \varphi$  will be radiated back to form the conjugate beam. Therefore, this two-stage mixing scheme can eliminate the leakage problems caused by the single-mixer approach, and has the advantage of never dealing with frequencies as high as  $2\omega$ .



There are still other sources which can contribute to the output phase error, namely, the leakage of circulators and reflection of antenna elements. In this paper, we solved this problem by separating the sampling and radiating antennas. For a true three-dimensional wavefront reconstruction setup, sampling and radiating should occur at the same point and, therefore, only one antenna is desired. Both circulator leakage and antenna reflection can be reduced to below 30 dB if they are specially designed for a specific narrow band. Also, for pulsed applications, wide-band operations can still be realized if the sampled signal and conjugate signal can be separated in time. This can be achieved by delaying the conjugate signal in a long optical fiber during the sampling period. During the radiating period, the mixer input is blocked and, therefore, the reflected conjugate signal will not enter the mixer.

In this paper, we have concentrated on generating phase conjugation using electronic-mixing arrays. This technique can also be extended to other nonlinear optics analogies. For example, by replacing the  $2\omega$  pump signal feeding the mixer in a phase-conjugate element with the sampled  $\omega$  signal, the element can generate  $2\omega$ , therefore, acting as a second-harmonic element. This type of electronic mixing arrays can perform free-space second-harmonic generation. Using different configurations for the basic elements, these electronic-mixing microwave arrays can provide very high effective  $\chi^{(2)}$  or  $\chi^{(3)}$ , which are not available in any natural material.

Due to the retro-directivity and automatic phase correction properties, microwave and millimeter-wave phase conjugation is useful in applications requiring automatic pointing and tracking and phase aberration corrections. We have also demonstrated that information can be transmitted in phase-conjugate signals without prior knowledge of where the targets are. Therefore, microwave and millimeter phase conjugation can be very useful for novel communications systems such as satellite links on moving vehicles and deep-space transponder applications. Another interesting application is to use these structures to combine the output power from many elements to form high-power beams with excellent mode quality.

In this paper, we have developed and demonstrated a new approach to achieve phase conjugation in the microwave and millimeter-wave regime. We have obtained similar results for both electrical and optical-interconnection techniques. The proof of two-dimensional free-space phase conjugation has been obtained by direct measurements of the output electric-field magnitude distribution at 10.24 GHz. Using a distorting medium and two sources, retro-directivity and automatic phase correction have been directly observed on the electric-field wavefronts. The capability of data communication using phase conjugation has also been validated by transmitting a 10-MHz modulated signal back to the two sources illuminating the conjugator. Furthermore, the conjugate signal has shown a 10-dB power gain, which is desired for communications applications. In the near future, we foresee many nonlinear optical techniques being extended to the microwave and millimeter-wave regime and also new microwave and millimeter-wave applications being developed using these electronic mixing arrays.

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