MICROWAVE PHASE CONJUGATION USING OPTICALLY INTERCONNECTED PHASED ARRAYS

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ABSTRACT

A new technique has been developed to achieve phase conjugation in the microwave and millimeter wave regime. Using optically interconnected microwave mixing circuits in conjunction with one-dimensional array antennas, two-dimensional free space phase conjugation at 10.24*GHz* has been observed and verified by directly measuring the electric field amplitude and phase distribution under various conditions.

INTRODUCTION

In general, phase conjugation utilizes the nonlinear susceptibility of a medium to reverse the phase factor of an incoming wave. The phase-conjugate wave propagates backward and has the same wavefronts as that of the incoming wave. This unique property is useful in many novel applications including automatic pointing and tracking, phase aberration corrections, and phase-conjugate resonators. To date, most of the phase conjugation development has been concentrated in the optical regime. Efforts to extend this technique to microwave and millimeter wave have encountered severe difficulties due to the small nonlinearity of natural materials and the low power density of sources at these wavelengths. In the search for alternative media suitable for the use in microwave and millimeter wave nonlinear optics, artificial media were found to have much larger nonlinearities than that of natural materials. Using shaped microparticle suspensions [1] and MEMS structures [2], volume grating formation for microwave phase conjugation has been demonstrated with degenerate four-wave mixing techniques. However, these media intrinsically suffer from slow response time and are sensitive to surrounding conditions. Therefore, they are not suitable for any practical systems and applications. In this study, we have developed a new technique to achieve microwave phase conjugation using arrays of optically interconnected antenna-coupled mixers as artificial nonlinear media. An 8-element array has been assembled to demonstrate two-dimensional free space phase conjugation at 10.24*GHz*. The results have clearly shown the retro-directivity and automatic phase correction characteristics of phase conjugation. Furthermore, these experiments have shown amplified conjugate-wave power up to 10 times of that of the incoming wave. This amplifying ability demonstrates the potential of such arrays to be used in novel communications applications.

CONCEPT

In this study, microwave circuits that combine antennas and microwave mixers effectively

0-7803-4471-5/98/$10.00 (c) 1998 IEEE

replace the nonlinear dipoles of a medium. The idea is to "sample" the incident wave at different positions of the wavefront 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 elements will be the phase-conjugate wave of the incident beam. This sampling concept was proposed in the 60's, but due to the lack of modern semiconductor and optical technologies, researchers did not have a practical way to realize the concept. [3] To understand how the conjugate signal can be generated at each element using microwave circuitry, let's consider the incident electric field at the j^{th} element:

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

where

$$\varphi_j = \mathbf{k} \cdot \mathbf{r}_j + \varphi(\mathbf{r}_j)$$

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

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

Now consider a 2ω signal delivered to the LO port of the mixer given by:

$$V_{j2} = Ce^{2i\omega t} + c.c.$$

This 2ω 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_{j1} that depends on *j*. If this happens, the sum of the excited field at each element will be distorted and will not form the conjugate beam. Optical interconnection is the crucial technology implemented to carry this 2ω microwave pump signal in phase to all mixing elements because of its low loss, light weight, and small size compared to the microwave counterpart. Using difference frequency generation in a mixer, the IF output current can be written as:

$$I_C \propto e^{2i\omega t} \cdot e^{-i(\omega t - \varphi_j)} = e^{i(\omega t + \varphi_j)}$$

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

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

When the sampling spacing is less than $\frac{\lambda}{2}$, the combined field $\mathbf{E}_C = \sum_j \mathbf{E}_{Cj}(\mathbf{r})$ forms the phase-conjugate wave on the sampling surface and therefore everywhere. Computer simulation has shown that the quality of the conjugate wave is limited by the size of the conjugation surface, not the element spacing, as long as the interelement spacing is less than $\frac{\lambda}{2}$.

DEMONSTRATION

To demonstrate the above-mentioned concepts, we have built an 8-element one-dimensional array with optical interconnects to deliver the 2ω pump signals. Figure 1 shows the configuration of each element. In this demonstration, the RF frequency is set at $10.24GHz$. A diode-pumped Nd:YAG laser is used as the light source. The optical wavelength is at $1319nm$, with a linewidth $\leq 5KHz$. The laser light is directed into a Mach-Zehnder optical modular and is modulated by the 2ω ($20.48GHz$) signal. The 2ω pump signal is delivered to each element using optical fibers. It is then extracted by a photodetector to be used as the LO signal for mixing. The amplitudes of all phase-conjugate elements are matched to within $\pm 2\%$. The phases are matched to within $\pm 0.2\,ps$ (0.2%).

To measure conjugate electric field distribution, a computer controls a receiving horn to scan the desired area. The detected signal is sent to a digital sampling oscilloscope and is compared to a fixed reference signal for

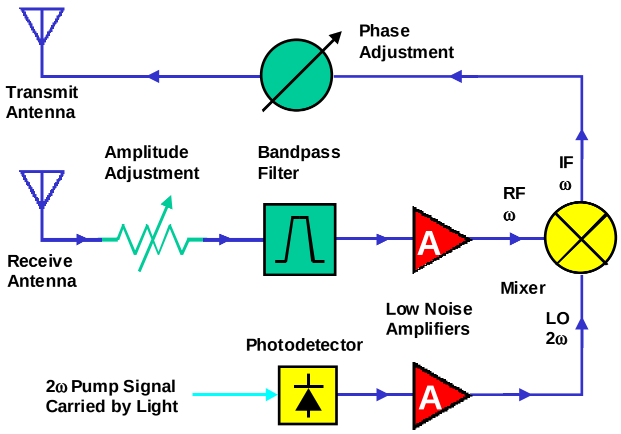

Figure 1. The configuration of a phase-conjugate element used in this study.

both amplitude and phase measurements. Figure 2 shows the results of one illuminating source. The first plot, marked as "Without Distortion", is obtained without anything in the microwave path and it clearly shows retro-directivity. However, due to the diffraction effects of the small array, the wavefronts do not focus back to the source. Note that the fainter fringes are caused by mixer leakage and can be eliminated by using a two-stage mixing technique. To demonstrate automatic phase correction, a distorting material is placed in front of the conjugator and the conjugate field is shown in the second plot, marked as "With Distortion". By comparing the fringes of the two plots, automatic phase correction is clearly demonstrated in the phase conjugate beam while the phase information is destroyed in the leakage signals. The same data is shown in Figure 3 as surface plots to exhibit the relative amplitude and destruction of the leakage signal. To further demonstrate phase conjugation with more complicated incoming wavefronts, two transmitting horns are used to create an interference pattern on the conjugator. The resulting conjugate electric field is shown in Figure 4. Again, retro-directivity and automatic phase correction have been demonstrated.

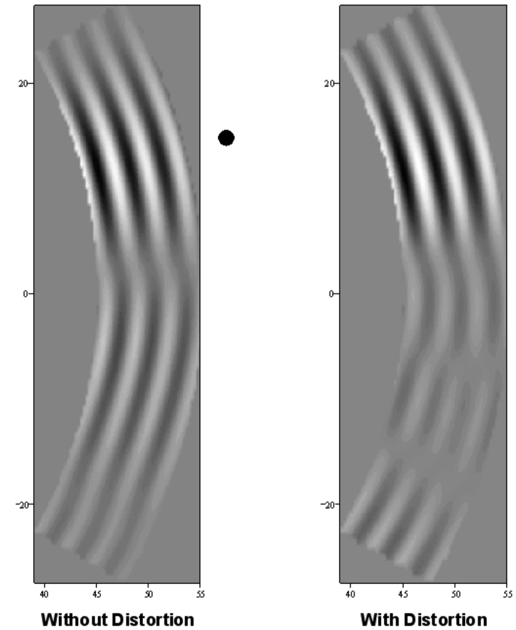

Figure 2. The contour plots of the measured phase-conjugate electric field of a source marked by the black dots. The conjugator is located on the left of each plot. Brightness represents electrical field magnitude. The wavefronts (fringes) travels from left to right. The conjugate beam demonstrates retro-directivity and automatic phase correction when a distorting medium is inserted in front of the conjugator. At the same time the leakage signals is distorted by the distorting medium.

CONCLUSIONS

We have demonstrated two-dimensional phase conjugation at 10.24*GHz* with diffraction limited results using an optically interconnected nonlinear microwave array. By extending this one-dimensional array into a two-dimensional surface, complete three-dimensional wavefront reconstruction can be realized at microwave and millimeter wave frequencies.

This work is supported by AFOSR under Dr. Howard Schlossberg and the DARPA sponsored NCIPT.

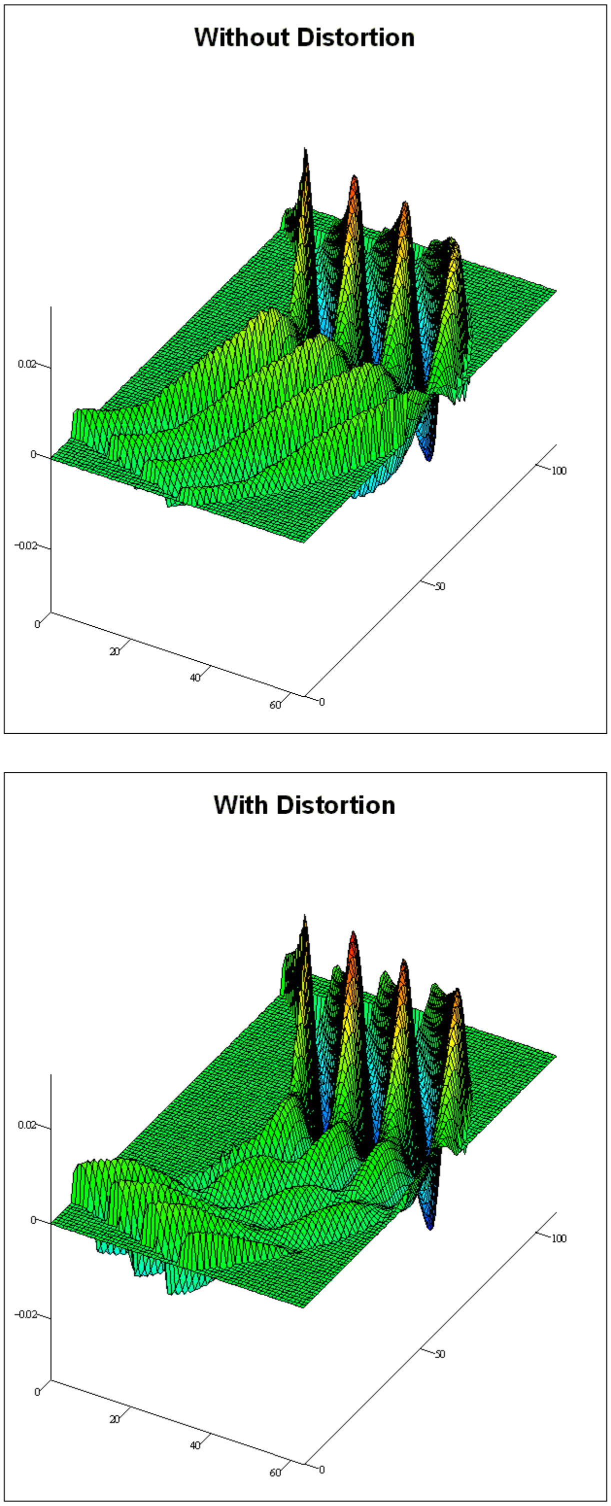

Figure 3. The surface plots of the data used in Figure 2. Height represents electric field strength and the white dots mark the source.

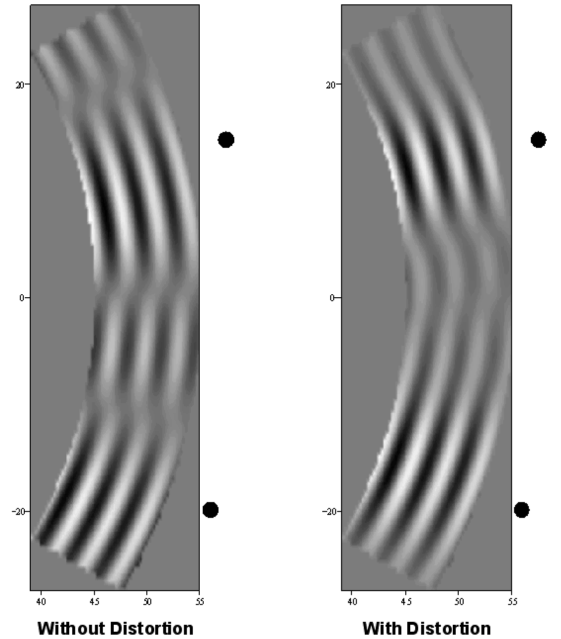

Figure 4. The contour plots of the phase-conjugate electric field of two sources marked by the black dots. They demonstrate multiple-source retro-directivity and automatic phase correction when a distorting medium is inserted in front of the conjugator. Leakage signals, down by about 10 dB, also appear adjacent to the conjugate signals and are distorted by the distorting medium.

[1] R. Shih, H. R. Fetterman, et al., "Microwave phase conjugation in a liquid suspension of elongated microparticles," *Phys. Rev. Lett.*, vol. 65, no. 5, pp. 579-582, 1990.

[2] B. Tsap, K. S. J. Pister, and H. R. Fetterman, "Grating formation in orientational optomechanical media at microwave frequencies," *Appl. Phys. Lett.*, vol. 70, no. 18, pp. 2475-2477, 1997.

[3] C. C. Cutler, R. Kompfner, and L. C. Tillotson, "A self-steering array repeater," *Bell Syst. Tech. J.*, vol. 42, pp. 2013-2032, 1963.