MICROWAVE PHASE CONJUGATION USING ANTENNA COUPLED NONLINEAR OPTICALLY PUMPED SURFACES

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ABSTRACT

An effort to extend phase conjugation techniques to microwave frequencies using optically injected active nonlinear elements is reported. Initial results were obtained using PIN diodes as detectors and microwave mixers as the nonlinear medium. Our current work is based upon optically injected HBTs as nonlinear mixing elements in conjunction with planar antenna arrays.

INTRODUCTION

Since its first demonstration, phase conjugation has been studied intensively. This technique 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 wavefront as that of the incoming wave. This property of phase conjugate waves is useful in applications requiring automatic pointing and tracking, phase aberration corrections, and other applications. Up to date, most of the development has been concentrated on the optical regime. Efforts to extend this technique to longer wavelengths have encountered severe difficulties due to the small nonlinearity of crystals and the low power density in this regime. In the search for alternative materials suitable for the use in microwave and millimeter wave nonlinear optics, artificial media were found to have much larger nonlinearities than in case of crystals. Using shaped microparticle suspensions, microwave phase conjugation has been demonstrated in a waveguide environment using degenerate four wave mixing (DFWM) techniques[1].

In a conventional DFWM experiment, the useful nonlinear polarization induced can be written as:[2]

$$P_{NL} = \chi^{(3)} E^3 \qquad (1)$$

Of all possible third-order terms that arise from E^3 we are interested only in terms which satisfy the frequency and momentum relation:

$$\omega_1 + \omega_2 = \omega_3 + \omega_4 = 2\omega, \ \mathbf{k}_1 + \mathbf{k}_2 = \mathbf{k}_3 + \mathbf{k}_4 \qquad (2)$$

where subscripts 1 and 2 arė for the pump beams, 3 is for the phase conjugate wave and 4 is for the incoming wave.

Our experiments reported here are based on three wave mixing (TWM). Generally, this technique utilizes the second-order nonlinearity. With a crystal as the nonlinear material, the induced nonlinear polarization can be written as:

$$P_{NL} = \chi^{(2)} E^2 \qquad (3)$$

The phase conjugate wave arises from the terms satisfy:

$$\omega_1 - \omega_2 = \omega_3, \ \mathbf{k}_1 + \mathbf{k}_2 = \mathbf{k}_3 \qquad (4)$$

where subscript 1 is for the pump beam, 2 is for the incoming wave and 3 is for the phase conjugate wave. Equation 4 sets up a very strong restriction on TWM in crystals: all three waves must be close to collinear. However, if the nonlinearity is strong enough such that the phase conjugate wave can be generated on a surface, the momentum relation is relaxed from equation 4 and thus TWM can be effective even the waves are not close to collinear.

In this paper, we present three concepts: 1. using microwave devices as conjugate phase generating elements via TWM.[3] 2. optical injection of the pumping signal of TWM to the microwave devices. 3. using an array of such optically pumped elements to generate phase conjugate wavefronts.

TH 3D

EXPERIMENT

To demonstrate the first concept, a triple balanced mixer was used as the nonlinear element. The mixer output signal can be written as:

$$V_{IF} = a V_{LO} V_{RF} \qquad (5)$$

Therefore this is similar to the TWM technique mentioned above. The experimental setup is shown in Fig. 1. The incoming wave (RF) carries a phase factor $\omega t + \varphi$ ($f = 10\text{GHz}$) and is mixed with $2\omega t$ (LO) to generate the conjugate phase: $\omega t - \varphi$ (IF). Both

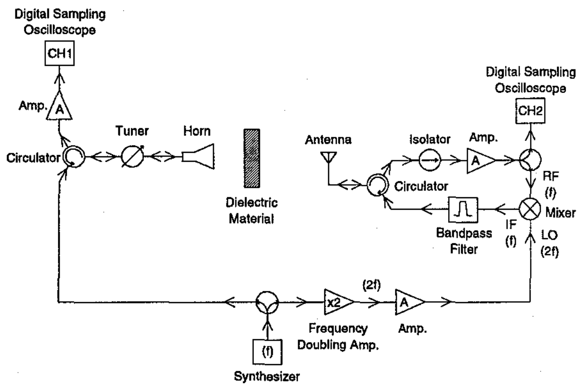

Fig. 1. Experimental setup of conjugate phase generation using microwave mixers.

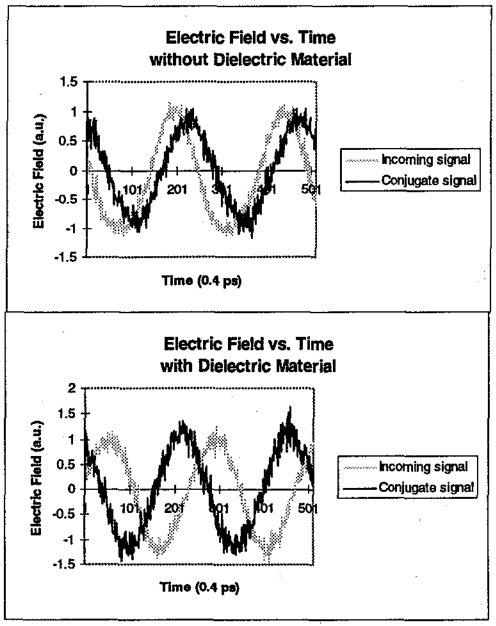

Fig. 2. Incoming and conjugate signals without and with dielectric material in the microwave path, monitored on digital sampling oscilloscope.

incoming and conjugate signals are monitored with a digital sampling oscilloscope. The results are shown in Fig. 2. The conjugate signal was virtually unchanged while the incoming signal was shifted due to the insertion of a dielectric material in the microwave path. This was expected because the conjugate signal carried a $-\varphi$ phase factor and this factor was canceled after the signal passed through the dielectric material the second time. This is also a one dimensional experiment and an array must be used to extend the experiment to three dimensions.

Optical injection is the key to making viable, low cost, simple arrays. The initial setup for the optical injection concept is shown in Fig. 3, uses fiber optics for the feeds, and eliminates the need for a doubling amplifier. The $LiNbO_3$ electro-optical modulator was biased at its transfer function extremum, therefore producing modulation at 2ω (20GHz) of the 1.3µm laser

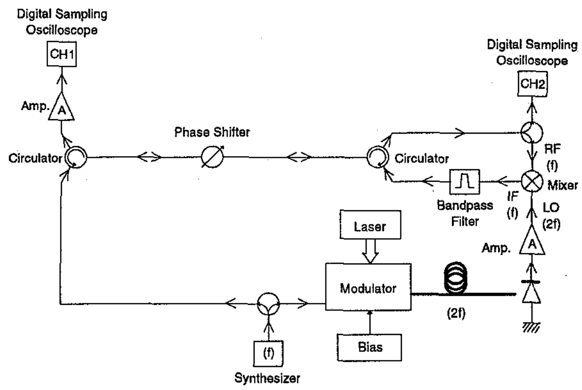

Fig. 3. Initial setup of optical injected conjugate phase generation.

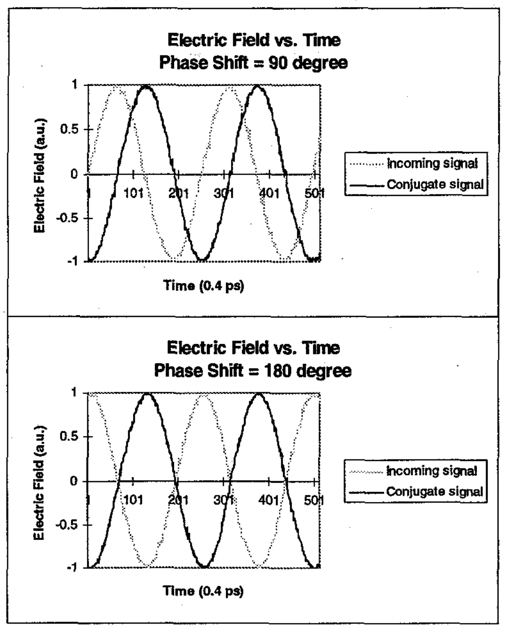

Fig. 4. Incoming and conjugate signals on the sampling oscilloscope. The conjugate signal was not affected by the phase shifter change.

beam. This light was then sent to a PIN[4] diode to generate the pumping signal 2ω. The 2ω signal was amplified and sent to the mixer to generate the phase conjugate signal. The results are shown in Fig. 4.

Optical injection of the pumping signal eliminates all field distribution problems that can occur in a microwave feed system. Another advantage of optical pumping is that it relieves the need of a high power, high frequency microwave source (2ω). Currently our study of this optical injection concentrates on using a single HBT[5] as the phototransistor and the mixer. The preliminary results show conjugate signals can be generated. The next generation edge coupled HBTs are being fabricated with an optical waveguide integrated in the base and collector depletion regions. The passive waveguide is designed to maximize input light coupling while the HBT is independently optimized for high speed mixing operation.

The previous mentioned experiments concentrate on generating phase conjugate signal at a single element. It can be proven that if the generated phase factor is conjugate to that of the incoming wave on a plane, it will be conjugate everywhere. Therefore an array of conjugate generation elements can provide the ability of generating phase conjugate waves. To demonstrate this concept, we built a two-element system to show the directivity originating from phase conjugation. The setup is shown in Fig. 5. Both transmitting horn and receiving horn are mounted on rotational stages. After setting up the transmitting horn at a specific angle, the receiving horn was moved around until the signal monitored on the sampling oscilloscope was maximized. The receiving horn angle was always equal to that of the transmitting horn. To prove this directivity was caused by phase conjugation instead of reflection, one element was turned

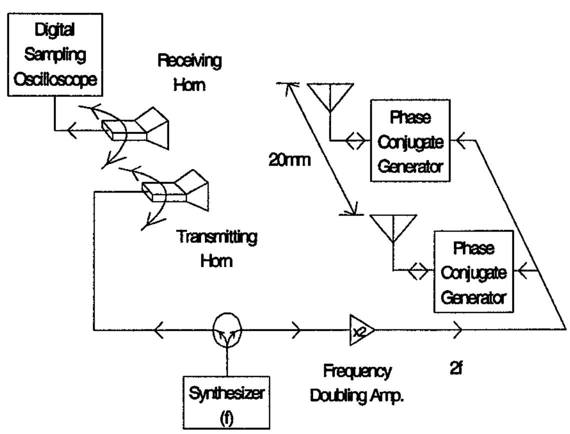

Fig. 5. Two-element array phase conjugation system. The phase conjugate generators are similar to the mixer circuit in Fig. 1.

off and the directivity disappeared. By moving the receiving horn around, we also found the FWHM width of the conjugate beam was approximately 60°. This agreed with the theoretical value calculated by two-element interference. When a dielectric material was inserted into the microwave path, the conjugate signal monitored on the sampling oscilloscope remained the same phase.

The optically pumped phase conjugate elements can be integrated to form microwaves nonlinear optically pumped surfaces (MNOPS) as shown in Fig. 6. These

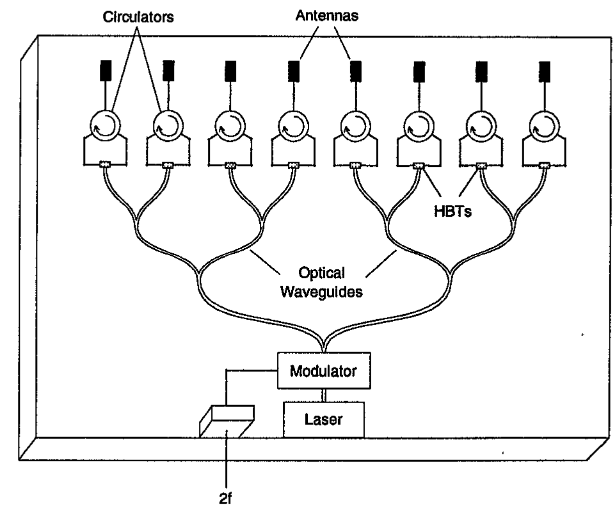

Fig. 6. Microwaves nonlinear optically pumped surface for two dimensional phase conjugation generation.

surfaces can be thought as artificial material with very strong second order nonlinearity.

CONCLUSION

We have demonstrated the concept of using optically pumped microwave devices in conjunction with antennas to generate phase conjugate waves in the microwave and millimeter wave regime. The optical pumping efficiency can be improved by using the next generation HBTs. As the number of conjugate elements increases, the directivity and the conjugate beam quality will be improved. In order to conjugate the wavefront, the radiating elements have to be spaced at most $\lambda/2$ apart. Currently, we are constructing a four-element array based on optically pumped TWM.

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