

Quasi-Optical Frequency Conversion Arrays

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ABSTRACT

A preliminary investigation of quasi-optical frequency conversion arrays is described. Using a diode-loaded dipole placed between two parallel conducting plates to simulate an array, we were able to demonstrate enhanced conversion efficiency into the second harmonic and obtain spontaneous parametric oscillation for certain array geometries. Sub-harmonic parametric oscillation was achieved by strongly driving the nonlinear antenna at a single pump frequency while the cavity length was adjusted for resonance at a subharmonic, and a well-defined threshold for this parametric down-conversion was observed.

I. INTRODUCTION

Quasi-optical power-combining is emerging as an attractive solution to the problem of limited power-handling capacity in millimeter-wave devices [1-3]. This paper proposes the application of these concepts to the realization of high-power frequency converters and parametric amplifiers. Some recent experiments at UCSB suggest that this can be accomplished using an array of coherently-pumped planar antennas, each containing a nonlinear parametric device. Impedance matching and frequency selectivity is achieved through antenna design and exploitation of the inherent mutual coupling between the antennas.

The preliminary experiments used a simple model consisting of a nonlinear dipole placed between parallel conducting plates (a Fabry-Perot cavity). According to image theory, the conducting plates simulate the response of the dipole in a large linear array (see figure 1). This not only simplifies the experiments, but also provides us with the following interpretation of mutual coupling in antenna arrays: the mutual coupling modifies the impedance of an antenna in a manner which reproduces the cavity mode structure, thus any antenna array is inherently frequency selective. If the antenna contains a nonlinear device which emits radiation at several frequencies, the filtering properties of the array are expected to have a profound influence on the output spectrum of the array.

II. INFLUENCE OF MUTUAL COUPLING ON EMISSION SPECTRA

First consider the behavior of the linear dipole driving-point impedance in the presence of the cavity. The mutual coupling that is introduced by the image elements can either enhance or inhibit emission at selected frequencies. For example, if the dipole is situated at the null of the standing cavity field, the radiation destructively interferes with image emission and the radiation resistance will decrease. Likewise, the radiation resistance is larger if the dipole is situated at the antinode of the cavity field, where there is constructive interference with image emission. The cavity length and dipole placement can therefore be tuned to selectively enhance emission at a certain frequency. This variation in radiation resistance can be quantitatively modelled using the induced EMF method from antenna theory [3,6]. It should be noted that the number of image dipoles in the equivalent

image array is related to the cavity losses; an approximate relationship has been derived as [3]

$$N \approx \frac{Q}{2d/\lambda}$$

where N is the number of array elements, Q is the cavity Q -factor, and d is the element (cavity) spacing.

The influence of mutual coupling on the spectral emission of a nonlinear array element was explored experimentally by embedding a p - n diode (the base-emitter junction of an NE6448 microwave BJT, with $f_r \approx 10$ GHz) at the feedpoint of the dipole used in the previous experiments. This particular device was chosen for convenience and not because of any desirable properties for this application. The experimental setup is shown in figure 2. The antenna was driven by an HP8350 sweeper, typically at frequencies between 8 and 9 GHz. The output of the HP8350 was fed through a bandpass filter with a bandwidth of 4 GHz centered at 8 GHz, and out-of-band rejection of 60 dB. The filter removes any harmonic distortion in the sweeper output as well as isolating the sweeper from the harmonics generated in the antenna. The spectral response of the antenna was observed using a waveguide horn and an HP8563 spectrum analyzer, with the horn at the broadside position to the image array. A double-stub tuner was used to provide a small-signal impedance match to the nonlinear device.

For a single element in free space the dipole radiates at the pump frequency and harmonics. However, the relative power in the second harmonic was observed to change dramatically when the element was placed within the cavity [3]. For example, if the cavity is tuned so that its fundamental mode is at the second harmonic, the pump frequency is below cut-off and subsequently the power radiated into the second harmonic frequency increases and the dipole radiation at the pump frequency decreases.

The array can also be used to enhance emission at frequencies that are not emitted by the isolated element, if the device is pumped strongly. For certain values of the cavity spacing and pump power, we observed dipole emission at the *sub-harmonic* and corresponding mixing products, as shown in figure 3a. This is a result of spontaneous parametric down-conversion in our setup, which can be explained as follows. When a nonlinear reactance is modulated at a pump frequency ω_p , it can easily be shown [7] that a negative resistance is induced at the pump subharmonic, $\omega_p/2$. This is the basis for degenerate parametric amplification [5]. If the embedding circuit satisfies the oscillation conditions at this frequency, spontaneous down-conversion will occur. Interestingly, we consistently observed this phenomenon for cavity spacings below cutoff for both the fundamental and sub-harmonic frequencies. In some cases we were also able to observe non-degenerate parametric oscillation, as shown in figure 3b. In this case one of the lower frequency components can be thought of as the "idler" signal in parametric amplifier terminology [5]. At no time did we observe parametric oscillation without the cavity present.

The driven parametric device can be considered as providing gain, with positive feedback supplied by the dipole-cavity interaction. If the array elements are spaced to avoid such positive feedback, a low-noise negative resistance parametric amplifier or frequency up-converter (with gain) can be created. The magnitude of the induced negative resistance is proportional to the pump power, suggesting that there should be a threshold for parametric down-conversion. This was verified by measurement of the sub-harmonic power versus pump power, shown in figure 4. For pump powers below threshold the subharmonic component of the dipole response is indistinguishable from the

noise floor. At approximately 35 mW, a sharp increase in sub-harmonic output is observed. As pump power continues to increase, the slope of the curve changes due to the change in diode impedance. When the pump power is very large, the negative resistance saturates and sub-harmonic power levels off. The maximum power could be slightly increased by adjusting the diode bias and double-stub tuner for a better impedance match under large-signal conditions.

III. CONCLUSIONS

To the extent that mutual coupling can be reproducibly controlled in a practical array, it may be possible to realize high power frequency converters and parametric amplifiers using large arrays of nonlinear devices, by adjusting the mutual coupling to provide a good impedance match and the desired frequency response. Each array element would have its own pump source, with all the pump sources operating coherently. This could be achieved in several ways, such as through a traditional array feed network, injecting the pump source quasi-optically, or using a coupled-oscillator array as shown in figure 5. In the latter case, coupling between the oscillators allows them to synchronize through the phenomenon of injection-locking [9].

Although the experiments presented in this paper simulated an end-fire array, the results should extend to broadside arrays as well. Conceptually, this is equivalent to placing our dipole between two magnetic conducting planes, which has a similar mode structure to the electric conducting cavity. Either case can be realized in a planar array by controlling the relative phasing of the pump sources. In the case of a coupled-oscillator pump array (figure 5), the relative phasing could be adjusted using recently developed scanning techniques [10].

The observed spontaneous down-conversion could provide a useful technique for frequency division or generating sub-harmonic mixing products. However, we consider the observation of parametric oscillations to be significant only as an indication that other parametric effects could be exploited in arrays. These include negative resistance parametric amplification and parametric up-conversion [5], where the regime of parametric oscillations would necessarily be avoided. Such possibilities are intriguing—parametric amplifiers have not historically been used as power amplifiers, despite low-noise and high efficiency, because all the power in the system would converge on a single small-junction diode. Since the junction area of the device must be kept small for impedance matching and reduced parasitics, there are fundamental limitations on the power-handling capacity of a single device amplifier. By combining a large number of parametric amplifiers in a quasi-optical array, we can take advantage of this high efficiency and high output powers while still keeping the power requirements of a single device to a reasonable level. Since the signals are coupled to free-space, there is very little parasitic loss in the system, which is important for noise reduction.

Additionally, the degenerate negative-resistance parametric amplifier is known to possess a *phase-sensitive gain* [5]. When the pump signal is fully coherent with the input frequency, the maximum gain of the amplifier can be as much as 6 dB greater than for a non-coherent pump source. Therefore if the pump phase can be made to track the incoming signal phase, the signal-to-noise ratio can be improved by up to 6 dB since non-coherent noise would receive 6 dB less gain. This same principle has recently been demonstrated in parametric laser systems [8], and could be achieved by making the degenerate parametric amplifier part of a phase-locked loop.

IV. REFERENCES

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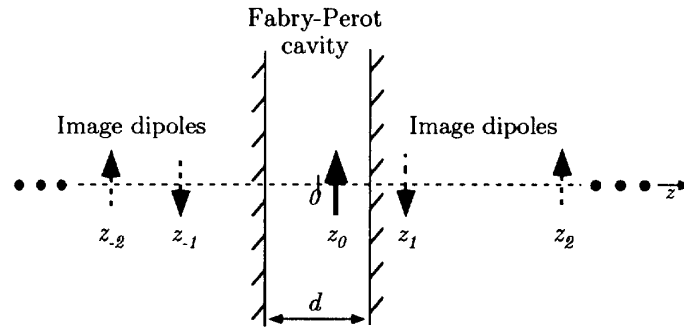


Figure 1 - Geometry for the dipole in a parallel-plate cavity, and the equivalent image array. Arrows denote the direction of current flow in the dipoles

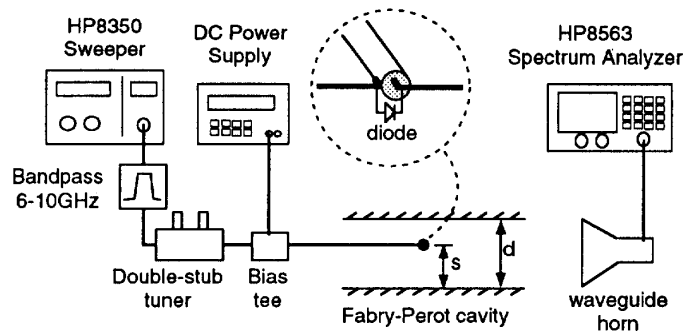


Figure 2 - Illustration of the experimental setup for observing the nonlinear dipole-cavity response. The HP8350 source plug-in was capable of delivering nearly 1 Watt at 8 GHz. The double-stub tuner was initially adjusted for a good match at small-signal drive levels using an HP8720 network analyzer.

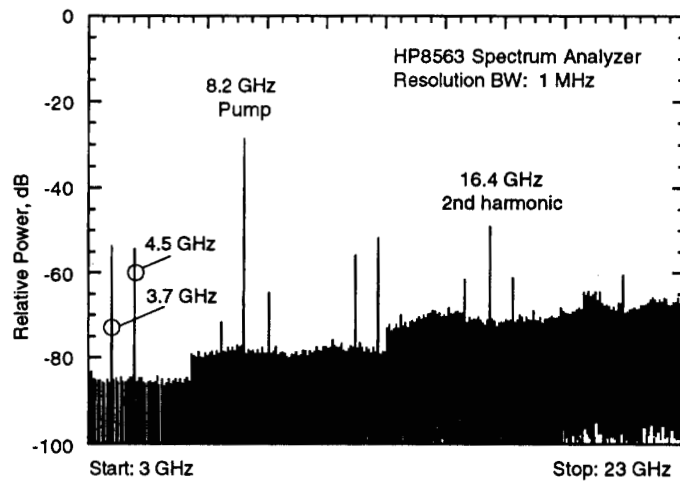
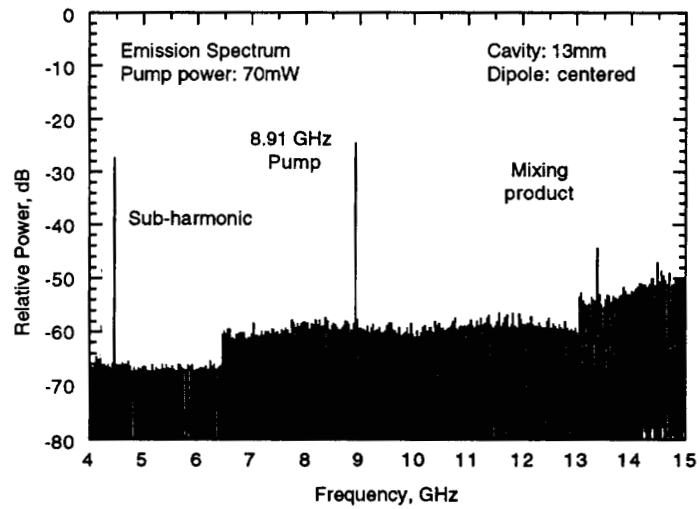


Figure 3 - Top: Dipole emission spectra under large-signal pump conditions, showing spontaneous parametric down-conversion (and mixing products) with cavity adjusted for resonance at sub-harmonic. Bottom: non-degenerate down-conversion was also observed with different cavity spacing and dipole placement.

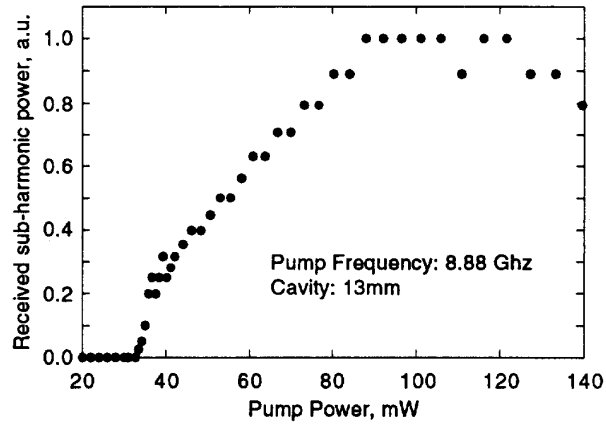


Figure 4 - Sub-harmonic power generated versus pump power. Above a threshold of approximately 35 mW, sub-harmonic power increases rapidly, then falls off as diode impedance changes under large-signal conditions.

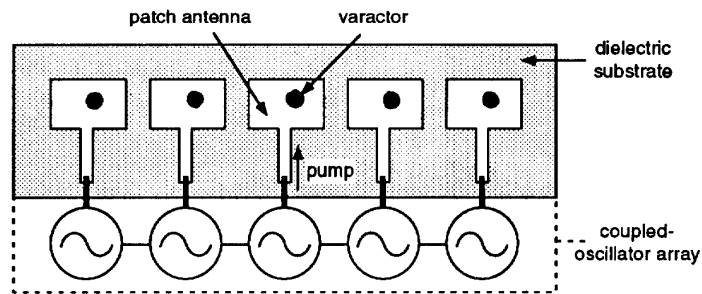


Figure 5 - Illustration of a quasi-optical frequency multiplier or parametric amplifier array. Varactor diodes embedded in patch antennas are driven by a local coupled-oscillator array. Antenna spacing, diode placement, and oscillator phasing determines the emission spectra.