Performance Analysis of the Photoparametric Up-converter Using Harmonic Balance Techniques

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Abstract: The photoparametric amplifier (PPA) operation is based on the non-linear CV characteristics of a photodiode and therefore, the mechanism constituting gain is highly non-linear and different to that in a conventional amplifier/mixer chain. A PPA has been successfully modelled and simulated using a nonlinear microwave simulator to perform harmonics balance analysis, which represented the photodiode model and nonlinear dynamic capacitance behaviour. The simulation predicted a PPA up-conversion gain as high as 27.57 dB, and this agreed with conventional theoretical analysis. In this article, the theory of operation, the device structure of the PPA, and its characteristic will be presented.

1. INTRODUCTION

As radio spectrum is increasingly overcrowded, optical links have been proposed as a viable alternative to microwave links. The laser wavelength must be chosen for optimum atmospheric transmission, and very importantly, the photodetection scheme has to be of high sensitivity and selectivity. An optical receiver's front-end design can be usually grouped into one of four basic configurations: (i) resistor termination with a low-impedance voltage amplifier, (ii) high impedance amplifier, (iii) trans-impedance amplifier, and (vi) noise-matched or resonant amplifier. The receiver performance that is achieved will depend on the devices and design techniques used. A photodiode with certain specifications can also perform as parametric amplifier, using photo detection and amplification in the single device, which is a unique amplification technique.

Although photoparametric amplification at microwave frequencies has been analysed [1] and demonstrated experimentally [2], it seems to have received little attention in literature since 1965. On the other hand, the basic technique has been applied using an optical pump [3] but not at microwave frequencies. Consequently, the development of a practical PPA not only requires a considerable theoretical analysis effort, but also a major experimental and modelling work. Thus, it is important to develop a proper model for the PPA, which is highly non-linear, in an attempt to simulate the device mechanism prior to practical implementation. As the circuit operation and amplification are based on the non-linear behaviour of a photodiode's capacitance-voltage characteristics, the harmonic balance technique is used to optimise amplifier up-converter performance.

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2. PHOTOPARAMETRIC AMPLIFICATION

The PPAs diode converts modulated light input to photocurrent, which is then parametrically amplified. The pump modulates the device capacitance, producing parametric amplification. Frequency conversion can be arranged. The system acts in a parallel way to a heterodyne detector, but without the noise penalty of resistive mixer techniques. The use of a photodiode in the parametric mode is the implementation of such a design philosophy, and hence the PPA is capable of improving the sensitivity with little penalty in terms of circuit complexity [4]. The theory of electronic parametric amplifiers is well established and mature [5,6]. An electronic parametric amplifier couples signal energy, at frequency ω_s, into a varactor via a tuned circuit. The pump at a given frequency ω_p, serves to modulate the capacitance of the varactor in such a way that the signal power is amplified by energy transfer from the pump. The output circuitry is designed to collect the amplified signal at the same frequency in degenerate mode, or at a higher frequency in non-degenerate mode (up-conversion). Thus, the parametric amplifier conventionally relates power flow. The PPA, in sharp comparison, has the power flow from an optical input to an electrical output. The approach used allows the signal energy to be externally coupled (by the incident radiation) directly in to the varactor. Figure 1 represents the small signal equivalent circuit of the PPA arrangement.

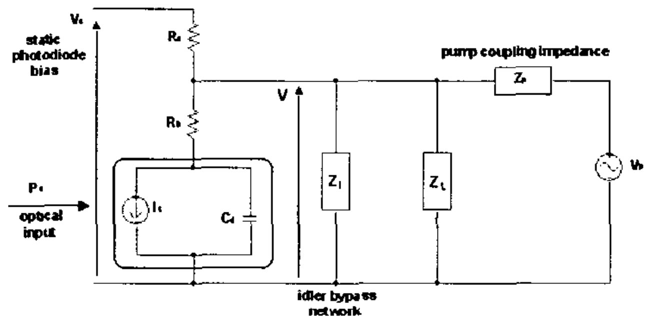

Figure 1: The equivalent circuit of PPA showing photodiode model with the time dependent capacitance, C_d.

The analysis of the photoparametric amplifier follows, by assuming four frequencies across the diode. They are; ω_s, ω_p, $\omega_{USB}=\omega_p+\omega_s$ and $\omega_{LSB}=\omega_p-\omega_s$, which resemble a four frequency parametric amplifier, where the Manley and Rowe general solution can be applied. The difference with respect to the classic case relates to the signal source, which is formed by current source embedded within the photodiode. There is also no tuned input circuit. The PPA theoretical analysis was presented in [2], the PPA corresponding conversion gain being given as;

$$A = \frac{\beta}{2}\left(\frac{\omega_i}{\omega_s}\right) \qquad (1)$$

The analysis predicts that the gain of the PPA in non-degenerate mode is directly dependent on the pump frequency ($\omega_i=n\omega_p \pm m\omega_s$) and the second parameter β, which is related to photodiode characteristics and pump input. This is consistent with the Manley and Rowe analysis ($A_v = \omega_i/\omega_s$), for which the term of $\beta(\beta<1)$ is a correction factor. As circuit operation is based on the non-linear behaviour of diode CV characteristics, the harmonic balance technique is used to optimise amplifier/up-converter performance. The technique allows the linear parts of the model to be described and simulated in the frequency domain, and the nonlinear parts in the time domain. Multitone harmonic balance analysis is applicable primarily to strong non-linear circuits that are exited by a single large-signal excitation source, such as the very high magnitude pump source, compared to the very small detected signal as in the case of the PPA. A commercial nonlinear microwave simulator, Aplac, was used to perform a multitone harmonic balance and large-signal/small-signal analysis of the generation and amplification of the detected signal.

3. PHOTODETECTION MODEL

A photodiode is similar in structure to the PN junction diode, except that its junctions can be exposed to external light, that forming a third optical "terminal". The conventional PN junction diode model (D) is used for the core of the photodiode model. The nonlinear depletion capacitance of the diode at the reverse bias condition C_d defined by the simulator represented the actual behavior of the capacitance quite accurately. The series resistance (R_c and R_a) at the cathode and anode side of the photodiode respectively are represents by R_{bulk}, the bulk resistance of the photodiode. Figure 2 shows the equivalent circuit for the photodiode model used in the harmonic balance simulation.

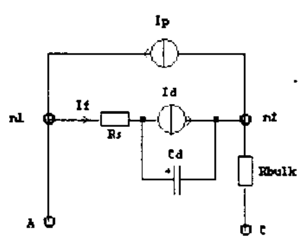

Figure 2: The illuminated photodiode model for simulation.

The current generator, I_p, models the light input terminal of the photodiode, and the photocurrent generation is given by equation 2, which is η = detection efficiency, W = incident optical power, h = Planck's constant and v = optical frequency, c/λ. The optical parameters were based on a laser source PMA Laser Diode Module PMA02/5208, with maximum output power 5mW, 20MHz amplitude modulation, and the wavelength was 850nm. The output current of the photodiode is represent by,

$$I_{pd} = I_d - I_p \quad \text{where, } I_p = \frac{q\eta}{hv}W \tag{2}$$

I_d is the dark current that flows when no signal is present, and I_p is the photo generated current due to the presence of incident light. The parameters of the model were obtained by a combination of device geometry estimation and parameter extraction from the manufacturer's data sheet of a commercial photodiode (IPL10040).

The diode's CV characteristic model has to be nonlinear in order for parametric amplification take place. To verify the nonlinear capacitance voltage characteristic of the proposed model, simulated and measured CV characteristics of the photodiode are plotted in Figure 3, (a) and (b) respectively. The diode capacitance was measured using a Boonton 72BD capacitance meter, which was able to measure with ±2% accuracy. The photodiode model shows close agreements with the measured results. The diode model tunability from the simulation is, ξ=8.89 and from the measurement, the diode tunability is, ξ=8.33, giving 6% differences. This excellent correspondence verified the validity of the proposed model.

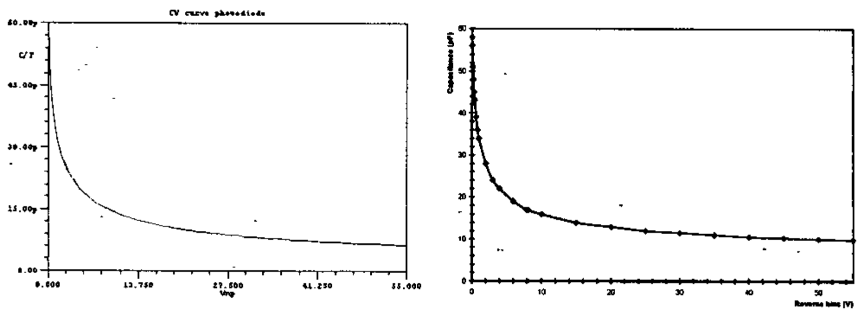

Figure 3: Simulated and Measured CV characteristics of the photodiode.

4. SIMULATION RESULTS

The schematic entries of the photoparametric amplifier model to perform the harmonic balance simulation are shown in [4]. The circuit was configured for a 1mW detected optical signal modulated at f_s=10MHz, and pumped by a large microwave source, f_p=900MHz, with a pump power of 20dB. Figure 4 (a) shows the output waveforms in the time domain. In the harmonic balance simulation, the output spectra were shown in figure 4(b), which clearly indicates the pump, and both lower and upper-sideband intermediate frequencies.

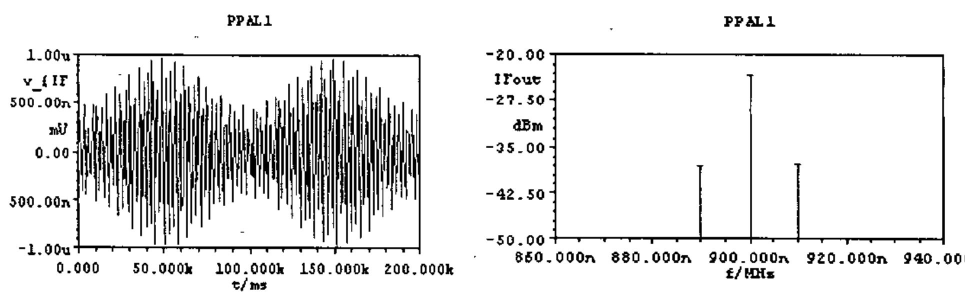

Figure 4: (a) PPA output waveform in the time domain, and (b) Output spectrum in the frequency domain

Refering to the PPA signal theory, the pump parameters are the main factor for the PPA up-conversion gain. However, since the PPA conversion gain was dominated by the ratio of IF frequency to signal frequency ($\nabla=\omega_i / \omega_s$), and for the PPA up-converter, $f_i=mf_p+nf_s$. The PPA circuit was simulated by varying the modulated signal frequency from 1 MHz to 20MHz, with 20 simulation loops to obtain 20 direct detected signals with 1MHz interval. In this simulation, the photodetector was receiving a number of different modulated RF signals. At the very much higher pump frequency at 800Mhz, no conversion loss occurs and the highest gain obtained was 27.57dB. It was predicted that no gain would occur if the PPA was detecting a higher signal frequency than 20MHz. However, there is another pump parameter that boosts the output signal power, which is the pump power. Figure 6 shows the variation of gain with pump power and its gain compression point. As expected, the gain increases with pump power below the compression point.

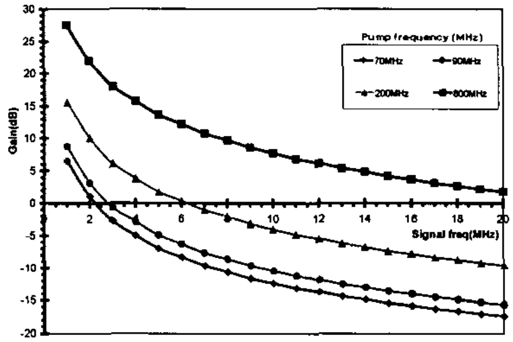

Figure 5: PPA up conversion gain for signal frequencies, f_s= 1-20MHz driven by LO at f_p = 70MHz, 90 MHz, 200Mhz and 800MHz, with 10dBm pump power level.

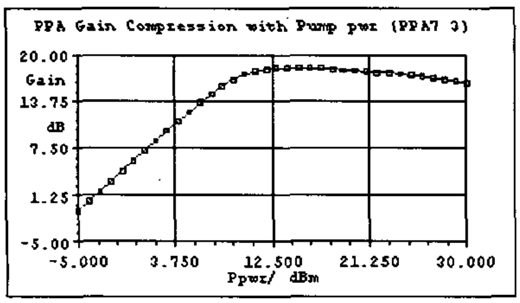

Figure 6: Simulated PPA gain compression with pump power , f_s=20MHz and f_p=900MHz

The experimental arrangement for measurement was using free-space optics. The frequency selection technique was by a pair of crystal filters, which had high-Q and were highly selective. For demonstration, it was decided to operate in the VHF frequency range, even though theoretically, the gain for the available frequency selection was not as high as expected from operation in the UHF band. Later, the practical parameters were used and applied to the PPA circuit model for the harmonic balance simulation. The measured and simulated results were in closely agreement, as shown in figure 7. Eventhough most of the measured results were lower than the simulated results, the majority fell within a 3dB error band. These findings show that the gain is directly related to pump input parameters. Therefore, if there is a limit to pump power, then gain may be recovered by appropriate adjustment of the ratio of the pump to signal frequency.

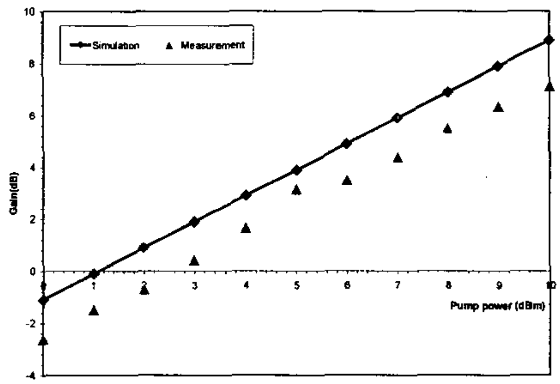

Figure 7: Simulated and measured results f_s=1MHz and f_p= 90MHz.

5. CONCLUSIONS

The photoparametric amplifier up-converter approach has been shown to work in a subcarrier multiplex system [2] and millimetre-wave fibre radio system [4]. Our study shows that, as far as noise performance is concerned, the photoparametric amplifier is generally superior to a comparable photodiode, followed by a conventional amplifier. In a conventional photodiode front end, consisting of a detector and high gain amplifier, the latter can be a significant source of noise. In comparison, a PPA has detection, gain and frequency translation all together, so that the noise sources are fewer and have lower overall significance. As the circuit operation is based on the non-linear behaviour of diode CV characteristics, the harmonic balance technique is used to optimise amplifier/up-converter performance. The PPA configuration was successfully simulated, which represented an actual photodiode model and nonlinear dynamic junction capacitance behaviour, and an in-house practical configuration was considered.

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