Nonlinear Analysis for Performance Characterization of a Photoparametric Amplifier

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Abstract- The photoparametric amplifier (PPA) combines optical detection and amplification within a single device. The amplifier operation is based on the non-linear characteristics of the photodiode and therefore, the mechanism constituting gain is highly non-linear and different to that in a conventional amplifier/mixer chain. The PPA has been successfully simulated using a nonlinear microwave simulator to perform harmonics balance analysis, which represented actual photodiode model and nonlinear dynamic capacitance behaviour. The simulation predicted a PPA up-conversion gain as high as 43dB and this agreed with conventional theoretical analysis. The up-converter gain has been shown to be directly related to the level of pump input and signal input. If there is a limit to pump power, then the gain may be recovered by appropriate adjustment of the ratio of pump to signal frequencies. In this article, the theory of operation, the device structure of the PPA and its characteristic will be presented.

1. Introduction

An optical receiver's front-end design can be usually grouped into one of four basic configurations: (i) a resistor termination with a low-impedance voltage amplifier, (ii) a high impedance amplifier, (iii) a trans-impedance amplifier, and (vi) a noise-matched or resonant amplifier. Any of the configurations can be built using contemporary electronics devices such as operational amplifiers, bipolar junction transistors, field effect transistors, or high electron mobility transistors. The receiver performance that is achieved will depend on the devices and design techniques used.

A photodiode with certain specifications can also perform as a parametric amplifier, giving photodetection and amplification in the single device, which can produce its own unique amplification technique. This can reduce the complexity of the receiver circuit and improve the performance of the system as whole to be less noisy. It may be seen that, in order to achieve the above operation, the photodiode is required to have photo detection capability and also behave as a varactor.

Although photoparametric amplification at microwave frequencies has been analysed [1] and demonstrated experimentally [2,3], 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 [4,5] but not at microwave frequencies. Consequently, the development of a practical PPA not only requires a theoretical analysis effort but also experimental work. Therefore, it has been the aim of this paper to discuss the device principle of operation and its parameters that allow the combined operations of photo detection and parametric amplification to take place.

2. Parametric Amplification

A parametric amplifier is a device in which gain is achieved by periodic variation of a parameter, usually capacitance, in the amplifier network. By this means energy at one frequency, the pump, is converted to energy at a second frequency, which is the chosen to be the signal frequency. In a typical parametric amplifier, a voltage-controlled capacitor is used, called a "varactor". If an electrical source (the "pump") changes or pumps the capacitance of the diode correctly, then energy from the pump can be used to amplify signals at another frequency or frequencies.

The theory of electronic parametric amplifiers is well established and mature [6]. The development of the theory of parametric amplification was achieved by Manley and Rowe. Manley and Rowe have derived a very general set of equations relating power flowing into and out of a one port passive and lossless device with a arbitrary ideal nonlinear reactance [7]. The main assumption is that the device is lossless, and power delivered at one frequency is balanced by power absorbed (in the tuned loads) at other frequencies. The Manley Rowe expressions are,

$$\sum_{k=o}^{\infty}\sum_{m=\infty}^{\infty}\frac{kP_{k,m}}{\omega_{k,m}}=0 \text{ and } \sum_{k=o}^{\infty}\sum_{m=\infty}^{\infty}\frac{mP_{k,m}}{\omega_{k,m}}=0 \qquad (1)$$

Where $P_{k,m}$ is the power flowing into the nonlinear capacitance at a frequency $\omega_{k,m}$. Active power $P_{k,m}$ flows into the reactance at the combination frequency ($k\omega_s \pm m\omega_p$). The active power is positive if it is fed to the nonlinear reactance and negative if it is delivered by the nonlinear reactance. Intuitively, when one external source of frequency ω_p is applied to the nonlinear capacitor, harmonic frequencies will be generated because of the nonlinear operation. Furthermore, in the presence of the two applied frequencies of ω_s and ω_p, numerous new frequencies of ($k\omega_s \pm m\omega_p$) are produced, where k and m are any integers from zero to infinity.

The manner of nonlinear interaction is similar to that which occurs in a nonlinear conductance device. The only new feature involved here is that no loss or negligible loss is considered with nonlinear susceptances. If power enters the nonlinear capacitors at the pump frequency, the same amount of power must leave the capacitor at the other frequencies through the nonlinear interaction. The Manley-Rowe expressions are another form of the conservation of energy law, if C is lossless [7].

3. Photoparametric Amplifier

A photoparametric amplifier is a device similar to electrical parametric amplifiers with the distinction that it uses a photodiode instead of a varactor to perform parametric amplification. Particularly, in an optical communication receiver, the parametric amplification technique is applied to the front-end optical receiver, as photodetection and parametric amplification can be achieved in a single semiconductor diode, as shown Figure 1.

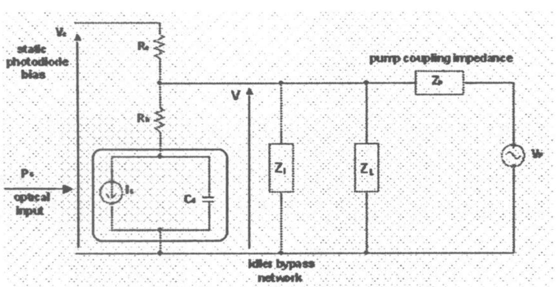

Figure 1: Basic structure of PPA

The photodiode converts modulated light input to photocurrent, which is then parametrically amplified. The pump modulates the device capacitance producing parametric amplification. Frequency conversion (down or up 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. In the up-conversion mode, the baseband is translated to a higher frequency, which is equal to the sum of the baseband plus pump signal (IF_{usb}), that will be selected, as shown in Figure 2.

Thus, the parametric amplifier conventionally relates power flow. The PPA, in sharp comparison, does not lend itself to the same treatment, as the power flow is from an optical input to an electrical output. 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.

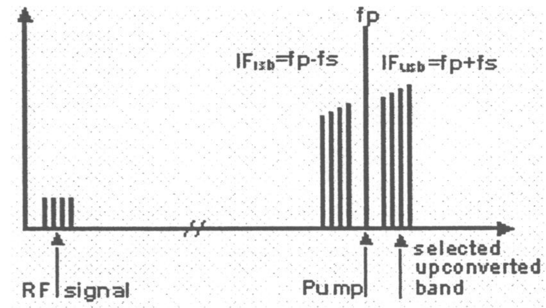

Figure 2: Frequency spectrum across the photodiode

The approach used allows the signal energy to be externally coupled (by the incident radiation) directly into the varactor. The difference with respect to the classic case relates to the signal source, which is formed by a current source embedded within the photodiode. There is also no tuned input circuit. The PPA theoretical analysis has been presented in [2], the PPA corresponding conversion gain being given as;

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

In this, the analysis predicts that the gain of the PPA in non-degenerate mode is directly dependent on 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.

4. Performance Characterisation

There are several important parameters indicated in PPA signal analysis which are controlled by the diode and the external circuits which have to be considered in designing the photoparametric amplifier. For the same diode condition and pump level, the operating regions for the photoparametric amplification possible are shown in Figure 3; frequency selection has to be chosen according to this chart. For parametric amplification, the reactance being pumped is a voltage dependent capacitance, so the effect of bias variation must be considered. Any change in bias voltage will result in a change in diode capacitance, and thus affect the behaviour of the amplifier. The analysis shown in Figure 4 indicated that the biasing may have a significant effect on amplification gain.

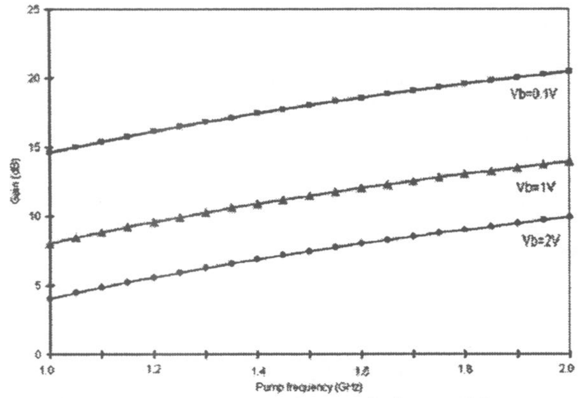

Figure 3: Graph region where gain is possible.

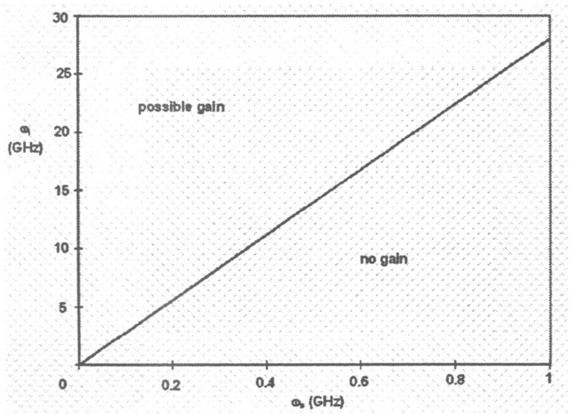

Figure 4: The effect of bias voltage towards PPA gain for ω_s=30MHz.

It is important to develop a proper model for the PPA, in an attempt to observe 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. 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, and forward and inverse Fourier transforms are used to bridge the two parts, as shown in Figure 5.

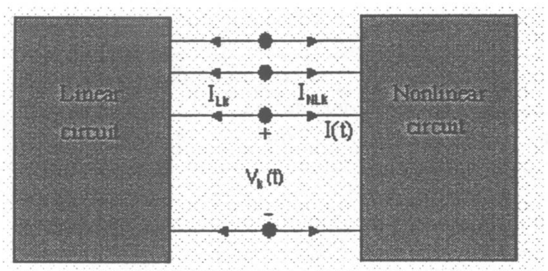

Figure 5: A circuit model illustrating the concept of harmonic balance.

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 [8]. The PPA was modelled using a commercial nonlinear microwave simulator to perform a multitone harmonic balance, or large-signal/small-signal analysis of the generation and amplification of the detected signal from an 850nm, 5mW-laser source.

The simulations were run by varying the microwave source frequency from 750MHz to 1500MHz, with 16 simulation points to obtain parametric amplification gain for each 50MHz-channel band. The circuit was configured for a 2mW detected optical signal modulated at 10MHz, while other parameters remained. The pump power was defined at 20dBm. In the time domain simulation, the output waveforms shown in Figure 6 were obtained.

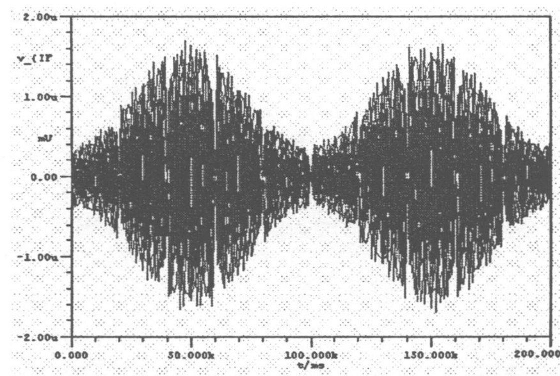

Figure 6: PPA output waveform in the time domain for modulated optical signal at 10MHz pumped by 20dBm LO varying from 750 to 1500MHz.

With respect to the frequency domain, Figure 7 shows 16 pump frequencies with their respective lower and upper sidebands. It clearly shows that the output power using a low pump frequency was much lower than the PPA output with a high pump frequency, even when driven at the same pump power level. Hence, the device is highly non-linear, and the output power is much affected by the pump frequency.

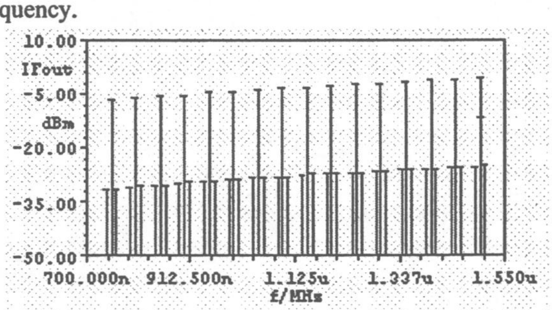

Figure 7: The intermediate frequencies spectra for a PPA detecting 10MHz optical signal and pumped by 20dBm LO varying from 750 to 1500MHz.

The length of the connecting transmission lines were positioned accurately and optimised. The upper-sideband of the intermediate frequency (IF_{usb}) was carefully selected, for which a power gain as high as 28.154dB was predicted for the PPA up-converter with a 1500MHz pump frequency. Figure 8 shows that the amplification was dependent, and increased with the pump frequency, as predicted earlier on the PPA small signal analysis.

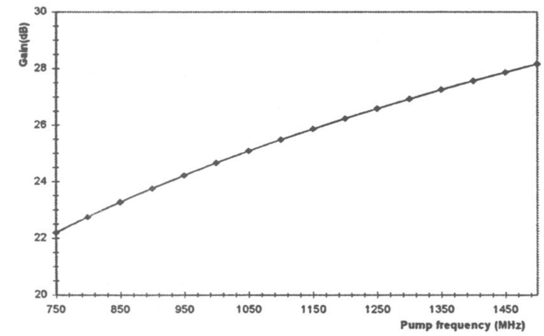

Figure 8: Simulated PPA up-conversion gain for 2mW detected optical signal modulated at 10MHz, pumped by 20dBm LO with varying from 750 to 1500MHz.

The PPA circuit was simulated by varying the modulated signal frequency from 1MHz to 20MHz, and the incident optical power was 1mW. In this simulation, the photodetector was receiving a number of different modulated RF signals. PPA was simulated for each modulated signal point with a pump frequency at 90MHz, and repeated for 70MHz, 200MHz and 800MHz pump frequencies. The simulation shows that the power gain was inversely proportioned to the detected signal frequency, for a 70MHz and 90MHz pump, conversion gain only being achieved by a signal frequency of less than 2MHz. At the higher frequency, the PPA will behave as a conventional microwave mixer, which has conversion loss. At the very much higher pump frequency of 800Mhz, there is no conversion loss and the highest gain obtained was 27.57dB. It was predicted that there would be no gain if the PPA was detecting a higher signal frequency than 20MHz. However, there is another pump parameter that will boost the output signal power, which is the pump power. The circuit was configured for a detected optical signal for f_s=5MHz, and pumped at 2GHz by varying the microwave source from –5dBm to 20dBm. The upper-sideband intermediate frequency (IF_{usb}) was carefully selected, for which a power gain as high as 43dB was predicted as shown in Figure 9.

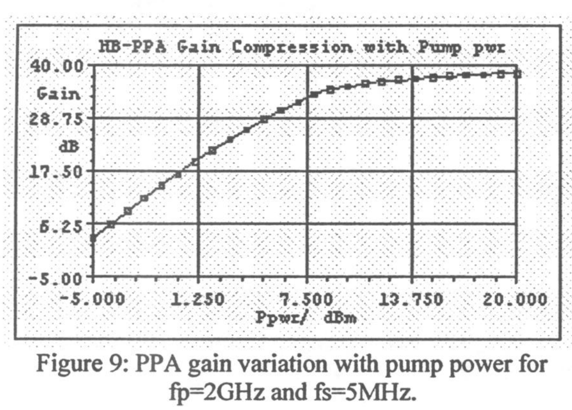

Figure 9: PPA gain variation with pump power for fp=2GHz and fs=5MHz.

Thus, the PPA gain are directly related to pump input, but very large pump power will make the photodiode forward bias and should be avoided. On the other hand, the larger the pump swings, the larger the negative bias on the varactor. Thus, as the pump signal is made larger, the diode capacitance decreases. Additionally, as the pump level is increased, the diode current will become higher. This will result in a rise in noise figure, due to shot noise effects. Therefore, such a large value of pump swing should be avoided. The simulation results are graphs showing the dependency of gain on the idler frequency and pump power. The important point here is that, the change in gain with detected signal frequency can be compensated by changing the pump parameters. Furthermore, the result in Figure 9 leads to the possibility of wideband operation through tuning the idler circuit appropriately.

The experimental arrangement of the PPA was using free-space optics. The frequency selection regime is by a pair of crystal filters, which are high-Q and highly selective. For demonstration, it was decided to operate in the VHF frequency range, even though theoretically the gain for the available frequency selection will not given as high as expected from operation in the UHF band. However, the practical results were very convincing since it given the same gain variation (due to biasing, pump and signal frequency variable) as theoretical and simulation work.

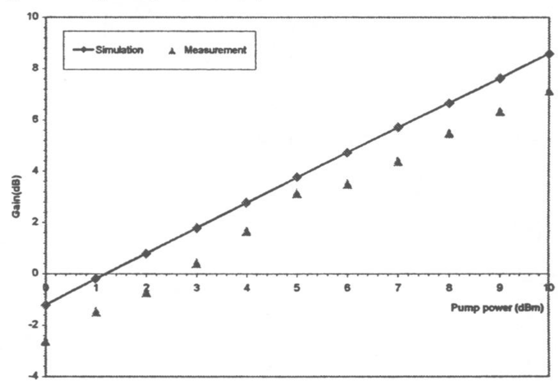

Figure 10: Simulation and measurement result for a PPA detecting 1MHz modulated signal and 90MHz pump frequency.

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. If the PPA temperature could be cooled down, noise due to thermal effects could be controlled and shot noise would remain as the predominant source in the PPA. For the PPA receiver, the determination of F will be the ratio of SNR for direct detection to the SNR due to parametric amplification. This shows that the photodetection SNR degrades by the photoparametric amplification. The system noise factor effectively due to shot noise for the photoparametric amplification within the junction diode will be,

$$F_{PPA} = \frac{I_s^2}{2qI_sB} * \frac{2qI_sB\left(A + \frac{R_b}{R_b + R_L}\right)}{AI_s^2}$$

(3)

For comparison purposes, by taking a typical PPA gain A=20dB, and both R_b and R_L is 50 Ω. The noise factor, F_{PPA} will be 1.005, which is only slightly more than one and, as a result the SNR of direct detection has 0.02dB degradation. The analysis shows that the PPA thus does not change the SNR power ratio very much, if the gain A>1. If the gain is unity, the PPA only acts as a no loss mixer, resulting in F=3 to the system. The larger the gain the smaller the degradation of the SNR by photoparametric amplification with respect to the photodiode as the direct detector. If A=100, only 1% SNR of direct detection will be degraded. The advantage of the PPA however, is the power gain associated with it. As a consequence, the noise of the amplifier following the photodetector is less significant. The PPA thus has a beneficial effect in many cases.

5. Conclusion

The analysis shows that the gain is directly related to pump input parameters. Therefore, if there is a limit to pump power, then the gain may be recovered by appropriate adjustment of the ratio of the pump to signal frequencies. The photoparametric amplification approach has been shown to work in subcarrier multiplexed systems [2] and a millimetre-wave fibre radio system [9]. The requirements of photoparametric amplification can be met if compromises in the usual optical detection performance are tolerated. The PPA has detection, gain and frequency translation all together, and the noise sources have lower overall significance.

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