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PHOTO-PARAMETRIC AMPLIFIER/CONVERTER IN SUBCARRIER MULTIPLEXED LIGHTWAVE COMMUNICATION SYSTEMS

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ABSTRACT

In this paper we shall report a novel type of low noise receiver for optical communication. The photo-parametric amplifier/converter may be used as part of a conventional wideband receiver, offering improved noise performance, or as a low noise detector/converter in a microwave subcarrier-multiplexed optical communication system. The receiver is based on the photo-parametric mode of operation, where a photo-detector is pumped at microwave frequencies and photo detection and parametric amplification are achieved simultaneously in a single device. Frequency conversion/ amplification is also possible to suit particular system applications.

(I) INTRODUCTION

Fiber optic transmission systems are now widely used in many fields, both for long haul and interoffice communications and also have application in other areas such as remote control of antennas, sensing, active array signal distribution, etc.[1]. A significant area amongst these is that of microwave subcarrier multiplexed systems in which many forms of signal are transmitted. In such systems the data rate limitation due to speed and cost of high speed digital electronics operating in gigahertz clock rates is no longer an issue[2]. The use of microwave frequency multiplexing offers up to 10GHz of transmission bandwidth and, as microwave subcarriers are independent of each other, the allocation of carrier frequency and respective bandwidth is fairly flexible and may be tailored to particular purposes throughout the band as well as in the overall system. Such an arrangement can offer a variety of services to the subscriber.

In a practical system, on transmission a number of microwave carriers are combined using conventional microwave electronics. These signals are used to amplitude modulate a laser diode which produces the optical signal for distribution. On reception, a photodetector followed by an appropriate low noise amplifier e.g. transconductance amplifier, may be used, or a fiber amplifier may precede the detection process. This allows recovery of the multiplexed signal which then has to be de-multiplexed in order to recover each subcarrier and therefore its information content. This may be a fixed arrangement, complimentary to the transmitting side, or a tunable one using a mixer and a local oscillator (analogous to tunable superheterodyne receiver). The second arrangement has many obvious advantages for subscriber services. The objective of this paper is to propose an alternative novel arrangement to the basic detector, pre-amplifier and mixer chain, in which a photo diode is used both for detection and in parametric mode and is to amplify the detected signal at a very low noise penalty. This may also have potential application in core 'optical ether' networks and be a competitor to more conventional WDM approaches.

(II) MODE OF OPERATION

The theory of all electric parametric amplifiers is well established and matured [3]. The main advantage of this type of amplifier is the ultra low noise performance. Although these amplifiers are capable of frequency conversion/amplification, they are mainly designed to operate with the same input and output frequencies, as this is the case in most practical microwave applications. However, in the proposed systems, the photo-detector is pumped, and photo-detected current may be up or down converted with the output signal at microwave frequencies. The system input /output frequencies may be configured to suit each system application. In a sub-carrier multiplex system, therefore, each sub-carrier may be selectively detected and amplified.

(II-a) Up-conversion/indirect baseband amplification
This system is suitable for direct detection/amplification of an amplitude modulated optical signal and the bandwidth extends from several hertz to some upper frequency limited by the the bandwidth of the output circuitry. The photoparametric upconverter arrangement essentially consists of a diode conjugately matched at the pump frequency to the circulator, nominally 50Ω. There is no input circuitry other than a small series capacitor forming a dc blocking filter. The block diagram of the basic circuit is shown in figure (1-a) The circulator provides a convenient method of applying the pump to the diode and extracting the signal, while at the same time isolating the load from the upconvertor. The upconverted output can be down converted to recover the signal by using a mixer, whose local oscillator originates from the same source as the pump via a suitable attenuator and phase adjuster.

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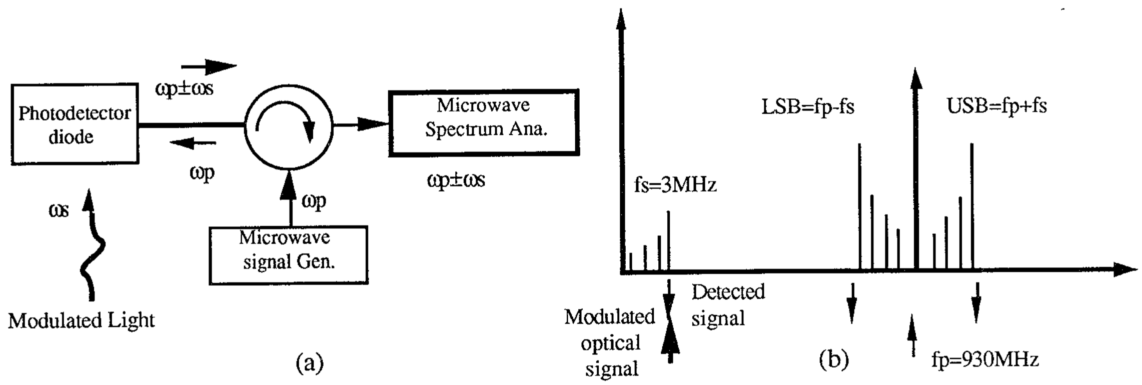

Figrure 1, (a) The experimentalset up and (b) the spectrum of signals across the diode

(II-a.1) Theory Let the current i_s correspond to the detected optical signal:

$$i_s = I_s \sin \omega_1 t$$

where

$$I_s = \eta P_S \frac{q}{h\upsilon}$$

where η is the quantum efficiency (typically ≈ 0.6) and P_S is the incident optical power, assuming 100% modulation and h and v are the Plank's constant and the optical frequency.

Assuming $\omega_p >> \omega_s$, it is possible to determine the current flowing into the load at sideband frequencies. It should be noted for typical cases, where the detected signal is of the order of a few kilohertz to a few megahertz, and the pump frequency is in the gigahertz region, it is difficult if not impossible, to prevent voltages and currents from being developed at $\omega_p \pm \omega_1$. This is not a disadvantage as the two components are fed into a mixer for down conversion.

The analysis details are as follows. There are four frequency components across the diode, ω_1, ω_p, $\omega_2=\omega_p-\omega_1$ and $\omega_3=\omega_p+\omega_1$ which resembles a four frequency parametric amplifier where.the Manley and Rowe[3] general solution can be applied. However there is a basic difference which makes the above amplifier different to the classic approach, and this is due to the fact that the signal source, unlike parametric amplifier, is a current source rather than a voltage source with finite impedance, and therefore a different approach is required.

(II-a.2) Analysis It is appropriate to consider that the device operates in two modes simultaneously. The first assumption is that changes in voltages across the photo-diode do not inhibit significantly (at least to first order effect) the fundamental relationship between input power and detected current. The second assumption is that the dynamic capacitance of the photo-diode is controlled purely by the pump. ie, the signal-induced changes in capacitance directly are small. The small signal equivalent circuit of the arrangement is shown in figure (2).

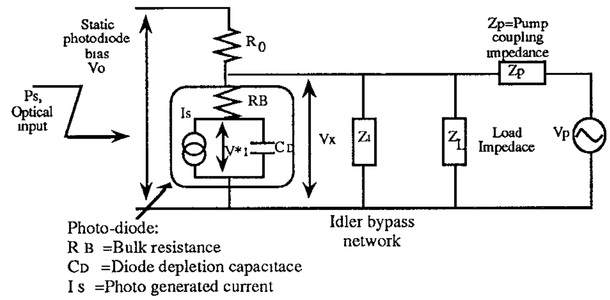

Figure (2) The equivalent circuit of pp-amplifier

From previous expression :.

$$I_s = P_s\left[\frac{\eta q}{h\upsilon}\right] = a_0 P_s \quad \text{for brevity}$$

Ps is the input optical signal, which, when taking the form of a modulated wave, may be represented as:-

$$P_s = P_0(1 + m\cos\omega_s t) \qquad \text{for } m \le 1 \text{ at modulating freq. } \omega_s$$

Let V^*_1 be the time varying voltage across C_D in figure 2. At frequency ω_p (pump):-

$$V_X = V_{P0} \cos \omega_p t = V_P$$

Thus,

$$V_1^* = \frac{\left(\dfrac{V_p}{j\omega_p C_D}\right)}{\left(R_B + \dfrac{1}{J\omega_p C_D}\right)} = \frac{V_p}{\left[1 + j\omega_p C_D R_B\right]}$$

DC voltage across $C_D=V_0$. Therefore, the combined effect of pump and DC bias is:-

$$|V_1| = V_1^* + V_0$$

Where V_1 is the overall voltage bias

$$|V_1| = V_0 + \frac{V_p}{((1 + j\omega_P C_D R_B)}$$

$$\text{Let} \qquad V_1 = -\left\{V_0 + \frac{V_p}{((1 + j\omega_P C_D R_B))}\right\}$$

as V_1 is usually a negative bias for the photodiode.

Now for the the PN junction (assumed), the depletion width 'd' is given by:-

$$d = \sqrt{\frac{2\varepsilon(V_x - V1)}{q}\left(\frac{1}{N_A} + \frac{1}{N_B}\right)}$$

for an abrupt junction diode, where V_X= barrier potential. Hence the depletion capacitance,

$$C_D = A\varepsilon\sqrt{\frac{q(N_A N_D)}{2\varepsilon(N_A + N_D)}\frac{1}{(V_x - V1)}}$$

and substituting for V_1 and taking the modulus of the complex quantity gives:-

$$\frac{1}{(C_D)^2} = \left(\frac{1}{D^2}\right)\left[1 + \frac{\frac{V_P}{(V_X + V_0)}\left(2 + \frac{V_P}{(V_X + V_0)}\right)}{1 + \omega_P{}^2 C_D{}^2 R_B{}^2}\right]^{\frac{1}{2}}$$

where $D^2 = \frac{\Delta^2}{(V_X + V_0)}$ and $\Delta = A\sqrt{\frac{q(N_A + N_D)\varepsilon}{2N_A N_D}}$

Therefore,

$$\Rightarrow \frac{1}{(C_D)^2} = \left(\frac{1}{D^2}\right)[1 + E\cos\omega_P t], \quad \text{where } E = \frac{V_P}{(V_X + V_0)}$$

The value of C_D is modulated by the pump in a complete fashion, therefore , the previous analysis gives no allowance for idler and circuit signal loading. If a general load of magnitude $Z_L = R_L + JX_L$ is connected in shunt with the device, the magnitude of the load voltage can be shown to be :-

$$|V_L| = |V_a|\frac{(R_L + X_L)^{\frac{1}{2}}}{(R_B + R_L)}$$

where

$$V_a = -J\left[\frac{aP_s}{D\omega_S}\right]\left(\begin{array}{l}\alpha + \alpha\cos\omega_S t + \beta\cos\omega_P t + \\ \frac{\beta}{2}\cos(\omega_P - \omega_S)t + \frac{\beta}{2}\cos(\omega_P + \omega_S t) + \ldots\end{array}\right)$$

and $\alpha = 1 - \frac{E^2}{16} - \frac{15}{1024}E^4 + \ldots\ldots$ and $\beta = \frac{1}{2}E + \frac{3}{64}E^3 + \ldots\ldots$

at which the optical input power P_0 is modulated. In consideration of the output in the upconversion mode the condition for gain is:-

$$\left(\frac{I_S}{\omega_S C_D}\right)\frac{\beta}{2} \geq \left(\frac{I_S}{\omega_i C_D}\right)$$

The corresponding upconversion gain is given by: $A_V \cong \left(\frac{\omega_i}{\omega_S}\right)\frac{\beta}{2}$

where the bracketed term represents the standard parametric upconvertor gain and the second parameter β is related to photodiode characteristics.

(III) PRACTICAL REALIZATION

In our previous attempt, carried out at University College and Bradford University, a photo-parametric up-converter amplifier was investigated and a low noise gain of 11 dB was demonstrated (figure 1-a,b). The above mentioned gain is the ratio of power in up-converted side bands to the detected signal across the diode where no microwave pump power is applied. The signal power was measured across a 50Ω load (input impedance of spectrum analyser, ie. identical load condition).

The pump frequency of this coaxial line setup was 930MHz and a narrow band laser driver circuit and a commercial laser diode were used as transmitter. Although the transmitter bandwidth limited the scope of experimental work, there was good agreement between results and theory. Some further practical work since has been carried out using a waveguide setup at X-band. This setup is primarily similar to figure(3), where the up-converted output is directly measured from the output of the upper sideband filter using a spectrum analyser (50 Ω). The results are illustrated in Figure (4 a,b). Inspection of these suggests that, although operating under non-optimum condition (noisy pump), a significant improvement in signal to noise ratio has been achieved (22dB of gain, 9dB of signal to noise improvement). Experiments show that the gain is proportional to the ratio ω_i/ω_S, as predicted in the aforementioned theory.

(IV) OTHER MODES OF OPERATION

The photo parametric amplifier can, however, be forced to operate in another mode, comparable to that of the negative resistance parametric amplifier, in which the output signal is taken at ω_S. This requires double conversion using an external mixer as suggested earlier or a secondary mixing by the varactor properties of the photodiode. The later arrangement is particularly attractive. Referring to figure (1b), in theory it is possible for an all-electric photo-parametric amplifier to choose any pair of the signals, or indeed any of the signals (excluding pump), as the input and the output. However, in such systems, if the signal frequency is fairly low and not in the microwave range, it is not convenient to have commensurate input and output frequencies, whereas in a photo-parametric amplifier, the separation of the input and output is not obviously an issue, as the input is generated inside the diode. This makes the direct baseband amplifier attractive in practical terms. The mechnism of operation is as follows:

The layout of the required hardware is shown in Figure (3). The photo-diode is pumped and the photo detected signal is up-converted and amplified. The upper and lower side-bands generated (idlers) are short circuited and phase adjusted to be reflected back. Across the diode, side bands are parametrically down converted to the baseband giving their energy to baseband signal. Separation of the lower and upper sideband requires some selective mechanism and ideally a pair of break wall low and highpass filters with their cut offs at the pump frequency. One of the practical limitations is that the finite Q of the filters will limit the lower frequency edge and effectively the amplifier will have a highpass response. Alternatively bandpass filters can be used in which case the upper edge of the amplifier bandwidth will also be limited by the bandwidth of the filters. The analysis is as follows:

With optional idler coupling circuits and a load circuit which filters out higher order components, the following holds:

$$V_{ai} = \left[\frac{\alpha P_S}{D\omega_S}\right]\left[\frac{\beta}{2}\cos(\omega_P - \omega_S)t + \frac{\beta}{2}\cos(\omega_P + \omega_S)t\right]$$

To obtain down-conversion gain, these must be first mixed with the pump, and normalised to baseband detection (for comparison purposes). The analysis leads to:-

$$\left(\frac{\beta^2}{2D\omega_S R_L}\right)\cos\omega_S t. \qquad \text{(ie. not dependant on } \omega_P\text{)}$$

Taking $D=C_{D0}=2\text{pF}$, as example, and $R_L=50$ Ohm, $\omega_S=1\text{MHz}$, $\beta=(E/2)=0.36$ (Pump power is 5mW), gives:- Av(relative)=20.1dB

The theoretical analysis also shows that amplification from other configurations is also possible where input and output frequencies are interchanged[4]. A prototype photo parametric down converter has also been tried with promising performance.

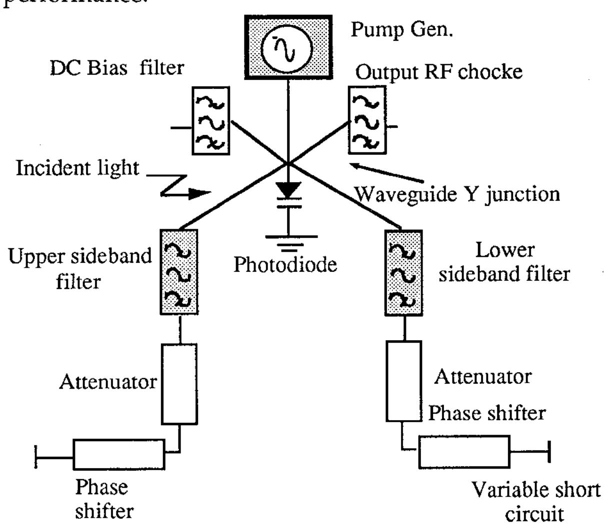

Figure 3, The experimental set up of direct baseband receiver

(V) CONCLUSION

A novel approach for the design of optical receivers is presented. The devices used are commercially available photo-diodes which are optimized for photo-detection. Clearly the starting point for the design of a tailor-made diode for the photoparametric mode of operation requires a theoretical study at device level. An attempt was made to address some of the issues involved both at circuit and device levels. The practical measurement carried out indicates that the performance of the photo-parametric up-converter described above is in a good agreement with the theory presented. Visual inspection of the amplified signal spectrum confirms low noise amplification. However, no quantitative measurements have been performed yet. It would be interesting to compare the results with those obtainable using the same diode followed by a classical low noise amplifier and quantify the noise performance improvement. An alternative approach has also been presented, along with theoretical analysis, and simplifies the required hardware.

(VI) REFERENCES

1-Green, R J, "Optical Communications; Past, Present and Future", IEE Electronics and Communications Engineering Journal, Vol.1, No.3, May/June 1989, PP 105-114.

2- Olshansky, R. , Microwave Sub-carrier Multiplexing.., IEEE Circuits and Devices Magazine, November 1988, PP8-13

3- Adams, D. K., "An Analysis of Four -Frequency Non-linear Reactance Circuits", IRE Transactions on Microwave Theory and Techniques, May 1960, PP. 274-283.

4- Khanifar, A., Green, R. J. "A new approach to Wideband Lightwave Communication Systems", International Symposium on Communication Theory & Applications, Session 16, Sept. 1991, Scotland.

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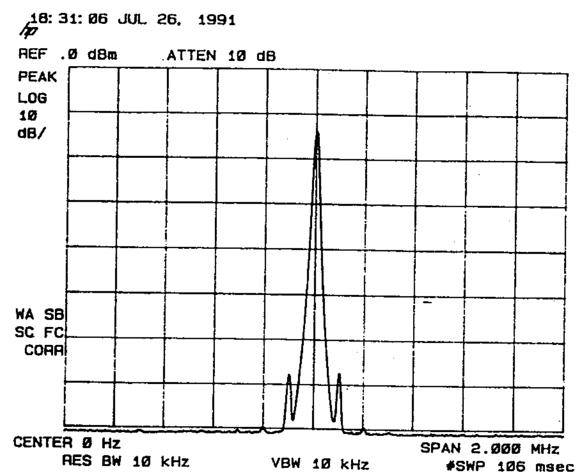

Figure 4a- Baseband signal; fs=0.1 MHz

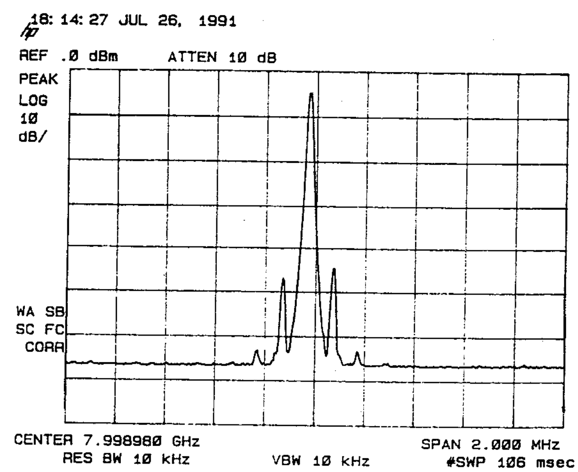

Figure 4b- Upconverted signal; fp=8GHz, fs=0.1 MHz