MICROWAVE AND MM WAVE PHOTO-CONDUCTIVE THREE-WAVE MIXERS FOR COHERENT DETECTION AND DOWCONVERSION OF OPTICAL SIGNALS

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ABSTRACT

Results are presented for InP and GaAs MMIC photo-conductive 3-wave mixers. In these mixers two optical signals offset by 33 GHz are multiplied together with a microwave signal, all within the same device, to produce a low frequency IF signal of a few hundred MHz.

The results are compared with the theory in which it is shown that these detectors are capable of operation up to mm wavelengths with 10% bandwidths and ideal sensitivities often better than ideal photo-diodes.

These mixers can be used for coherent detection and downconversion of optical signals and as optoelectronic phase detectors.

INTRODUCTION

Modern coherent optical communications systems require high performance opto-electronic detectors and mixers to satisfy the system requirements. Ultrafast photo-diodes require special processing to obtain the thin structures while maintaining adequate absorbtion . These devices are very static sensitive and have to be combined with special networks if balanced mixing operation is required. Further the bandgap and semiconductor material have to be chosen carefully to obtain the optimum speed/sensitivity combination. This often restricts the use of materials and if Flicker noise is important for example when used as a phase detector for phase locking semiconductor lasers together then surface effects in the three five compounds usually cause high Flicker noise corners in excess of 50 MHz.

Within this paper it will be shown analytically that photoconductive three wave mixers can often be used where it is shown that the recombination time is usually not important and that reasonable bandwidths can be obtained with a sensitivity sometimes better than a perfect photodiode.

A photo-conductive 3 wave mixer is shown in Figure 1. A coplanar or microstrip transmission line is formed on a high resistivity or semi-insulating semiconductor and a gap is etched to produce a photo-conductor (1). Two optical beams are incident on the gap producing a conductance which varies at the beat frequency. An RF local oscillator is applied to one terminal and is arranged to switch the direction of the carriers. This is therefore a single balanced mixer with both an optical and electrical local oscillator (1,2,3,4). A small capacitor can be placed between the centre electrode of the output and the ground plane to ensure that most of the RF voltage appears across the gap. The output signal can then be directly connected to a high frequency transimpedance amplifier.

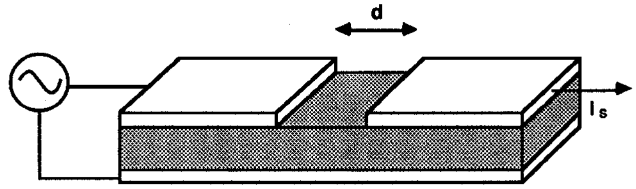

Figure 1. Photo-conductive Detector

Detector Analysis

For coherent detection:
The input optical signal consists of the signal field

$$e_s(t) = E_s \cos \omega_s t \quad [1]$$

and a strong optical local oscillator field

$$e_L(t) = E_L \cos(\omega + \omega_s)t \quad [2]$$

The total field incident on the photoconductor is

$$e(t) = Re[E_s e^{j\omega_s t} + E_L e^{j\omega_L t}] = Re[V(t)] \quad [3]$$

The rate of change of carriers is equal to the (generation rate - the recombination rate):

$$dN_c/dt = -N_c/\tau_o + G \quad [4]$$

where $G = K\ V(t).V^*(t)$, N_c is the number of excited carriers and τ_o is the average carrier lifetime. The number of excited carriers then becomes:

$$N_c = K\,\tau_o[E_s^2 + E_L^2 + 2E_sE_L \cos(\omega t-\phi)/\sqrt{(1+\omega^2\tau_o^2)}]$$
$$\text{where } \phi = \tan^{-1}(\omega\tau_o) \quad [5]$$

KE^2 can be calculated by letting $P_s = 0$ and equating the generation rate = recombination rate as this is the steady state condition ($P/hf = N_c/\tau_o$). When an RF signal $V_{rf}\cos\omega_{rf}t$ is applied to one terminal then as:

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$$I_s(t) = N_c(t)e\upsilon/d \quad [6]$$

where e is the charge on an electron, d is the length of the gap and υ is the instantaneous velocity which is equal to:

$$\upsilon = \mu V_{rf}Cos\omega_{rf}t/d \quad [7]$$

where it is assumed that the carrier relaxation time << $1/\omega$.

The wanted part of the signal (the lower sideband) will then be:

$$I_s(t) = (V_{rf}/d^2).(\eta e \tau_o \mu \sqrt{(P_sP_L)}/(hf \sqrt{(1+\omega^2 \tau_o^2)}) Cos(\omega - \omega_{rf}) \quad [8]$$

Note for maximum conversion efficiency V_{rf}/d is a constant and set to arrange that the carriers travel at saturation limited velocity at the peaks in the RF waveform. **The sensitivity is therefore inversely proportional to d.** This can also be written in the form

$$I_s(t) = (\tau_o / \tau_d).(\eta e \sqrt{(P_sP_L)}/(hf \sqrt{(1+\omega^2\tau_o^2)}) Cos(\omega - \omega_{rf}) \quad [9]$$

For $\omega^2 \tau_o^2 >> 1$ this equation simplifies to:

$$I_s(t) = (1/ \omega \tau_d).(\eta e\sqrt{(P_sP_L)}/hf) Cos(\omega - \omega_{rf}) \quad [10]$$

Which means that the main requirement for the semiconductor is to have high mobility and short transit time. **The recombination time is not necessarily important!** (5) Further although the output current is rolling off at 3dB per octave for ω_S when the signal is transposed down to baseband, **the response is very flat** because an offset of $\pm$ 1GHz at 33GHz only consists of a change in ω of 6% ($2\delta f/\omega$). It should be noted however that long recombination times decrease the DC on resistance which may increase the Shot noise due to optically generated DC voltages.

A table of the typical values for the transit times, voltage required for operation at saturation limited velocity and $1/\omega\tau_d$ for a 2 μ gap photoconductor (assuming the bulk mobilities which may be higher than those achievable) is shown in table 1.

Table 1

Material	Minimum volts/μ for sat velocity	Velocity μ/ps	Transit time for 2 μ gap	$1/\omega\tau_d$ at 10GHz
GaAs	0.3V/μ	0.2μ/ps	10ps	1.6
InP	1V/μ	0.25μ/ps	8ps	2
Si	3V/μ	0.1μ/ps	20ps	0.8

The sensitivity of an ideal 2μ InP photo-conductive three wave mixer photo-conductor at 10 GHz is better than an ideal photo-diode detector because to produce the same function the photodiode would have to be followed by a double balanced mixer which would have a conversion loss of 6 dB.

The sensitivity of a photo-diode is:

$$I_s(t) = (2).(\eta e\sqrt{(P_sP_L)}/hf) Cos(\omega - \omega_{rf}) \quad [11]$$

If the photodiode was driven by an RF voltage directly the photodiode would normally be slow and have high conversion loss.

Vertical structures can be considered but it can be shown that there is an optimum value of αl for best sensitivity and this is very dependent on the optical frequency.

The calculations so far have only been for the intrinsic photo-conductor. In fact the structure has three parasitic capacitors in a π configuration where it has been shown that the impulse response time constant (2) for high on resistances with a DC drive voltage is $\tau = Z_0(2C_1+C_2)$.

The direct low frequency Shot noise does not occur due to the balanced RF signal however the Shot noise around the RF carrier frequency will be downconverted.

Care needs to be taken not to induce the transfered electron effect as this will introduce noise. It may however be possible to use this as the local oscillator.

COHERENT DETECTION OF STIMULATED BRILLOUIN BACKSCATTER

InP and GaAs Photo-conductive three wave mixers have been used to coherently detect and downconvert Stimulated Brillouin Scattering (SBS) from an optical fibre.

The system is shown in Figure 2.

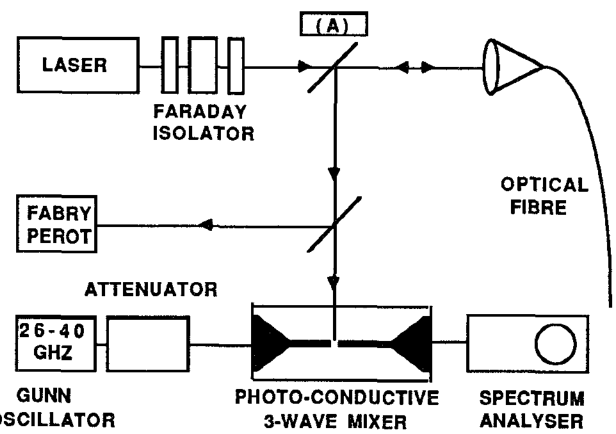

Figure 2. Experimental System for the Detection of Stimulated Brillouin Backscatter

Light from a single mode 514 nm Argon Ion laser was launched into a Hi-Bi single mode optical fibre via a glass slide beam splitter. A Faraday optical isolator was placed at the output of the laser to ensure adequate isolation between the laser and the backscattered light from the fibre. The front face Fresnel reflection and stimulated Brillouin backscatter from the fibre were directed on to a confocal Fabry Perot spectrum analyser and photo-conductive 3-wave mixer, by the glass slide beam splitters. The photo-conductive mixer was driven by a tunable 100 mW waveguide Gunn oscillator (26 - 40 GHz) via an attenuator and waveguide-to-OSSM adapter. The frequency range of the Gunn oscillator was chosen to span the expected Brillouin frequency shift: approximately 33 GHz for fused silica at 514 nm. The output from the mixer was then fed directly into a 50 Hz to 1.8 GHz spectrum analyser.

When the system is roughly aligned the Fresnel reflection was seen on a Fabry Perot spectrum analyser(3,5). The Stimulated Brillouin line appeared when the input coupler was adjusted to optimise the launched light into the core of the fibre. The microwave local oscillator frequency was set to 33 GHz which caused the beat frequency of the two optical waves to be down-converted into the pass band of the RF spectrum analyser. This detected signal could be tuned down and then up again in frequency as the microwave local oscillator was varied from one side of the Stimulated Brillouin signal to the other side. We believe however that the microwave local oscillator may injection lock to the Brillouin signal at frequencies within 200 MHz. This is possibly due to the fact that the photo-conductor does not have perfect ohmic contacts and therefore some of the optical signal was detected and coupled back into the oscillator. This effect can be reduced by using microwave isolators or by altering the attenuation, however the later lowers the signal level. The signal level can be improved by inserting a high power optical local oscillator via a mirror at A. This arrangement can be used to measure the temperature distribution along a fibre as the frequency of the Brillouin line is temperature dependent (3,5,6,7,8,9). The authors have built distributed optical fibre temperature sensors using Raman Backscatter (10).

The structure of the InP Photo-conductor is shown in Figure 3. The tapers at either end are used to interface the detector with OSSM connectors.

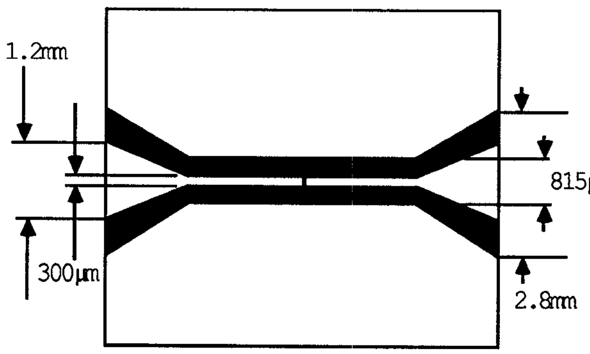

Figure 3. Coplanar photoconductive mixer

The results are shown in Figure 4. The optical local oscillator was approximately 3mW and the signal power 0.6mW . The output electrical signal power is -90 dBm. (The signal was amplified by a 10 MHz to 1 GHz amplifier with a gain of 24.7 dB before injection into the spectrum analyser). For a gap of 20 μ, the theory predicts an electrical output power of -80.6 dBm where η is assumed to be 0.5 (incorporating reflectivity) and the rms voltage across the gap is estimated to be 0.5 volts rms.

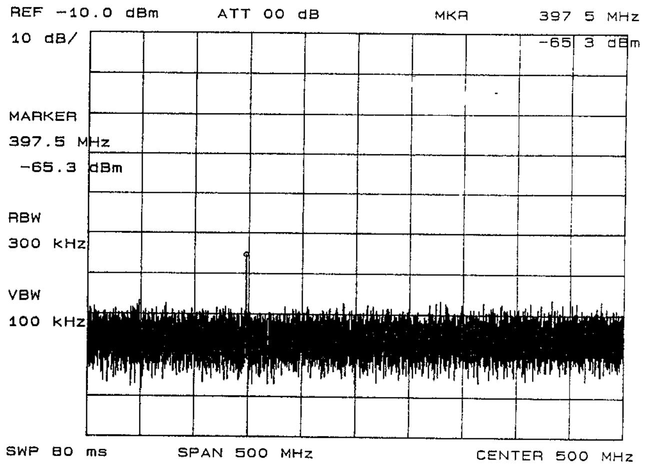

Figure 4. Output from InP Photo-conductor

The discrepancy between theory and experimental results may be due to non optimum optical alignment, innacuracy in the value of the voltage across the detector, reduced surface mobilities and the parasitic capacitors. The impulse time constant for the parasitic capacitors in the detector operated as a high resistance switch with a DC drive is of the order of 10 ps (2).

Similarly a 4 micron GaAs photo-conductor has been made on the Plessey Foundry service where the Polyamide was removed around the active area. The results are shown in Figure 5 where -85dBm is obtained under the same drive conditions. The theory predicts -64.2 dBm. The discrepancy is believed to be due to the mismatch between the RF LO caused by the bonding of the chip to the alumina jig. A further test was performed where the optical input power was increased to 11mW Local oscillator and 3 mW signal power. The electrical output was found to increase by 10 dB as shown in Figure 6.

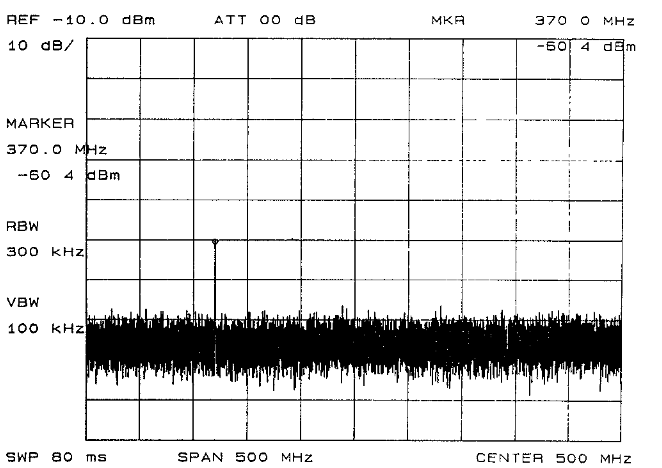

Figure 5. Output from GaAs Photo-Conductor

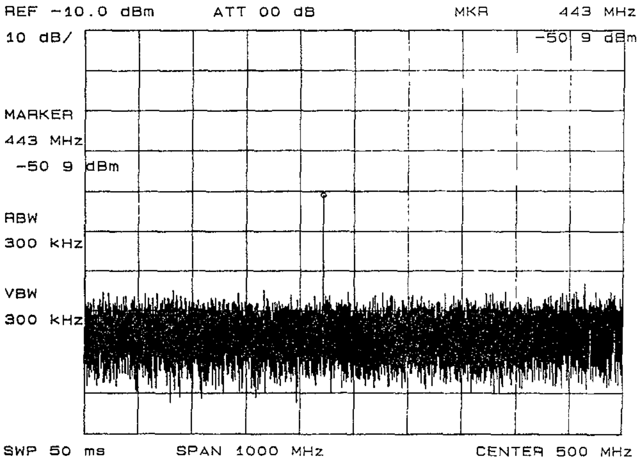

Figure 6 Output from GaAs Photo-conductor with increased optical drive power

IMPROVEMENTS

The system is currently being improved by installing an isolator at the output of the RF LO an E-H impedance matching network and directional coupler with diode detector.

The devices are being optimised to obtain maximum RF LO across the gap. It is planned to build the local oscillator on chip to interface directly with the photo-conductor and to investigate oscillators containing the photo-conductor within the resonator using oscillator structures similar those shown on Page 259-264 of Reference (11). Parallel configurations are being investigated where the gap is between the centre conductor and the ground plane. This would allow the use of one RF LO for many optical signals.

CONCLUSIONS

Theories have been presented which suggest that photo-conductive detectors can be used to detect and dowconvert the beat frequency of two optical signals with reasonable sensitivity and bandwidth. Experimental results from InP and GaAs detectors have been presented.

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