Noise model for photodetectors with distributed optical amplification and absorption

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1.-Introduction

Photodetectors for high-speed long-haul optical communication systems are required to present high bandwidth, high responsivity, low noise and high saturation power. We are currently studying a novel type of photodetector, that we call Traveling-wave amplification photodetector (TAP detector), in which optical gain and absorption are combined in a distributed way in a traveling-wave structure, in order to obtain efficiencies higher than one while maintaining high-speed characteristics [1,2]. Due to their distributed nature, these devices are also able to produce a higher output photocurrent with the same peak optical power, thus avoiding detector saturation. The price for these advantages is a small noise penalty. In order to successfully simulate both this noise penalty as well as the effects of gain saturation in the performance of TAP detectors, a distributed model including effects of spatial non-uniformities is necessary. We present here such a model when applied to TAP detectors with a parallel configuration (see Fig. 1), in which a single optical waveguide exhibits gain in the center and absorption on the sides, for optimum overlap between the peak of the mode and optical amplification, while at the same time presenting slow absorption for high saturation power.

2.-Carrier density calculation

The carrier density in the active region of a parallel TAP detector can be related to the input power P_{in}, and to the injected pump current I_{pump}, by means of a rate-equation model that takes into account also spatial non-uniformities [3]. Longitudinally dividing a device of length L into M sections, we can evaluate the carrier density vector $\mathbf{N}=(N_1,N_2,\ldots N_M)$, whose j-th element represents the average carrier density in the corresponding section, by solving the following system of non-linearly coupled rate-equations:

$$\frac{I_{pump}}{e\cdot M\cdot w\cdot d\cdot L_j} = R_{sp,j}\left(N_j\right) + R_{stim,sig}\left(\mathbf{N},P_{in},\lambda_{sig}\right) + R_{stim,ASE}\left(\mathbf{N}\right),\ \ j=1,2,\ldots,M, \qquad (1)$$

L_j, w and d being the length, width and thickness of the active region, respectively. The right hand side contains three terms expressing recombination rates per unit of volume and time. The first one accounts for spontaneous recombination, and therefore depends only on the carrier density in section j. The second term quantifies the stimulated recombination due to signal photons, and depends also on the signal wavelength λ_{sig} and on the carrier densities $N_1,N_2,\ldots N_j$, from the input of the device to the considered section. The third term is the stimulated recombination rate due to ASE photons, and is a function of the whole carrier density vector $\mathbf{N}$. The carrier density profile can be retrieved for different values of I_{pump} and P_{in} by using a gradient least-squares method of fast convergence. A 32-section analysis gives an accurate approximation of the actual spatial variations of the carrier density for device lengths up to 1mm.

3.-Distributed noise model

We can find the position-dependent average optical power and optical power variance by dividing a TAP detector longitudinally in sections of length dz, and treating each one of them as a semiconductor optical amplifier (SOA) with constant gain and stimulated emission rate. This is achieved by using a semiclassical particle-like formalism [4] in each section, which allows us to write differential equations satisfied by the average signal power, both forward- and backwards-propagating amplified spontaneous emission (ASE) average power, and average photocurrent. Using the values for gain and stimulated emission rate calculated as explained above, the effects of gain saturation in the detector efficiency and ASE power generation can be quantified. As shown in Fig. 2, the efficiency of parallel TAP detectors with lengths between 100 and 500μm will exhibit a 1dB compression point between ~0.5 and ~2.5mW.

Similar differential equations can be written for the signal and ASE power variances, allowing us to calculate the total optical noise, shown in Fig. 3 to be dominated by ASE-ASE beat noise up to 10μW, and by ASE-signal beat noise for higher powers. We can also write a differential equation for the photocurrent variance, from whose solution the output signal-to-noise ratio (SNR) and noise figure (NF) of parallel TAP detectors, shown in Fig. 4, can be calculated. The output SNR is ~20dB for input power ~10μW. Parallel TAP detector performance will be optimum (not limited by noise or saturation) between –20 and 0dBm.

4.-Conclusion

We present a new semiclassical particle-like distributed noise model that takes into account spatial non-uniformities due to gain saturation, and used it to calculate the noise penalty introduced in parallel TAP detectors, as well as the range of powers for their optimum performance.

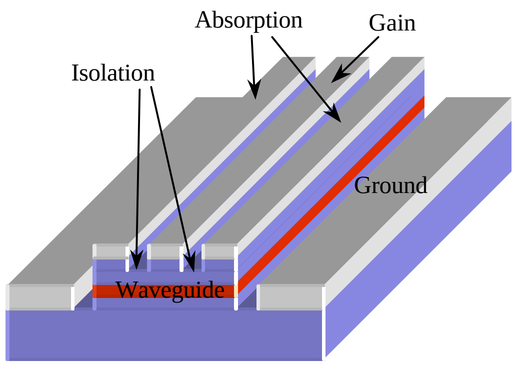

Fig. 1: TAP detector with a parallel configuration.

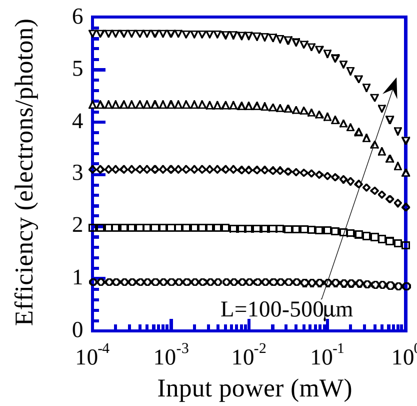

Fig. 2: TAP detector efficiency vs. input power for different device lengths (pump current=60mA/mm).

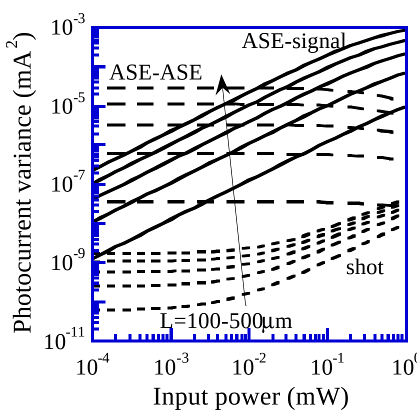

Fig. 3: Photocurrent noise contributions vs. input power for different device lengths (pump current=60mA/mm).

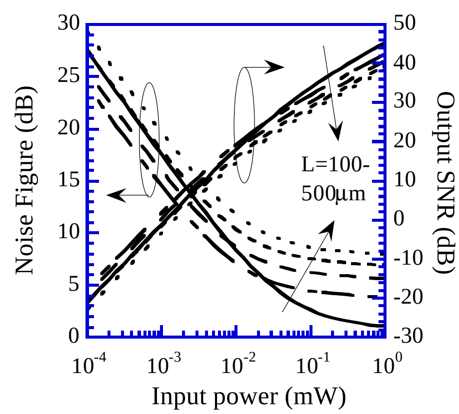

Fig. 4: Output SNR and noise figure vs. input power for different device lengths (pump current=60mA/mm).

References

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