Mole Fraction Effect on Semiconductor Optical Amplifier Specifications

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Abstract

Semiconductor optical amplifier had been studied theoretically using the traveling wave equation. The study took into consideration the many parameters that could affect the operation of amplifier, such as mole fraction, noise figure and material gain have been studied theoretically for the suggested amplifier in the wavelength of   1.55 μm. The results show that gain material peak was shifted when injected current and wavelength were varied. An interesting result of the noise figure was found to be minimum at the operating wavelength of 1.55 μm.

Keywords: Amplifier noise, noise, noise figure, noise measurement, wideband semiconductor optical amplifiers.

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I. INTRODUCTION

Light can be sent long distances through high quality fiber with little dispersion or attenuation. The 1.5μm wavelength that is commonly used in communication systems corresponds to a frequency of $2*10^{14}$Hz. A bandwidth of even 0.1% of this carrier, 100GHz, is wider than any encountered in electrical systems. Optical systems are also much less susceptible to interference in comparison to electrical systems. A combination of the above factors has made optical communications, the method of choice for distances over 100 km [1].

Semiconductor optical amplifiers (SOA) are interesting devices for a wide range of applications in optical communication systems. The vertical-cavity design gives these devices a number of advantages over in-plane devices, such as high coupling efficiency to optical fiber, low power consumption, small form factor, and the possibility of fabricating 2-D arrays on wafer [2]. Furthermore, the technology allows for on-wafer testing and is compatible with low-cost manufacturing and packaging techniques. These advantages all draw from the fundamental geometrical differences between the vertical cavity and the in-plane designs. In a vertical-cavity structure, the optical mode passes perpendicularly through the different material layers. Consequently, the electrical field is always parallel to the plane of the active layers. This makes vertical-cavity SOA insensitive to the polarization of the signal light. It also makes the gain per pass very small, on the order of a few percent [2].

Optical amplifiers are incorporated into optical communication systems in order to increase transmission distance or receiver sensitivity. However, amplification is achieved at the cost of compromised signal integrity [2]. The noise figure is a figure of merit for the SNR degradation, and hence for the power penalty associated with the introduction of the device into a transmission system. This makes the noise figure one of the most important properties of optical amplifiers for their applications in optical communication systems [2]. The inhomogeneous line broadening of EDFA can be eliminated by using SOA but at the cost of high noise figure [3]. The noise figure deserves a detailed study because the inversion factor is not directly related to the gain of the SOA [4]. Well-known properties of SOAs have been used to obtain the gain uniformity, and very low level of noise figure [5].

The mole fraction has a main effect on material gain calculations as can be seen in other published papers [6][7] in order to calculate the noise and the noise figure of SOA, the material gain of the SOA has been estimated also for different mole fraction in this work.

II. THEORY

The theoretical basis for the noise figure of optical amplifiers is reviewed, and a consistent approach to determining the noise figure of cascaded components is developed. It is shown that when the noise figure is defined in terms of the input and output signal-to-noise ratios, the formulation provides a consistent theoretical formulation for measurement techniques using optical and optoelectronic measurement methods. The paper concludes with a review of measurement techniques for characterization of the noise figure [8].

The undesired optical power fluctuations (intensity noise) introduced by optical components cause transmission impairments in optical communications systems [8]. This noise

can be characterized indirectly by measuring the optical field power spectrum and using an approximate model to evaluate the intensity noise. Alternatively, optoelectronic detection is used where a photodetector converts the optical power into an electrical signal and the accompanying noise is analyzed using standard electronic techniques. Characterization of the noise figure of an optical amplifier can be straightforward or complicated depending on the context in which the noise figure data are employed. For the simple situation where the noise figure is used to quantify the contribution of the Erbium doped fiber amplifier (EDFA) to the accumulation of amplified spontaneous emission (ASE) in a cascade of amplifiers, optical measurement methods are commonly used. In cases where the complete noise figure is required, such as when optical reflection-induced intensity noise must be considered, optoelectronic measurement methods should be used. The model presented here applies to both optical and optoelectronic noise figure measurement techniques. Reduced to its simplest form, it is shown to be consistent with the noise figure as defined by the IEC(SC86C, Working Group 3)[8], the international standards body responsible for optical amplifier noise figure definitions. That definition has been adopted by the ITU-T (International Telecommunications Union-Telecommunications) and is in use by the major test instrument and optical amplifier equipment manufacturers.

Pertinent geometrical and material parameters for the device under consideration are given in Table 1. The InGaAsP direct bandgap bulk-material active region has a material gain coefficient given by [6]:

$$g_m(\nu_k, n) = \frac{c^2}{4\sqrt{2}\pi^{3/2} n_1^2 \tau \nu^2} \left(\frac{2 m_e m_{hh}}{\hbar(m_e + m_{hh})} \right)^{\frac{3}{2}} x \sqrt{\nu - \frac{E_g(n)}{h}} (f_c(\nu) - f_v(\nu)) \qquad \ldots \qquad (1)$$

where

- c speed of light in a vacuum.
- ν optical frequency.
- n_1 active region refractive index.
- τ radiative carrier recombination lifetime.
- $\hbar$ Planck's constant h divided by 2π.
- m_e m_{hh} conduction band (CB) electron and valence band (VB) heavy hole effective masses, respectively.
- n CB carrier (electron) density.

Recalling equation(1), the factors can be affected by the mole fraction are; the energy gap [$E_g(n)$], and hence optical frequency (ν), the active region refractive index (n_1), quasi_Fermi level separation.

The bandgap E_g energy can be expressed as[6]:

$$E_g(n) = E_{go} - \Delta E_g(n) \qquad \ldots \qquad (2)$$

E_{go} the bandgap energy with no injected carriers, is given by the quadratic approximation [6,7]:

$$E_{go} = e(a + by + cy^2) \qquad \ldots \qquad (3)$$

where a and b are the quadratic coefficients and e the electronic charge. $\Delta E_g(n)$ is the bandgap shrinkage due to the injected carrier density given by[6]:

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$$\Delta E_g(n) = eK_g n^{1/3} \qquad \qquad \ldots \quad (4)$$

where K_g is the bandgap shrinkage coefficient. The value of K_g used in the model is taken to be slightly less than the value for $In_{0.15}Ga_{0.85}As$. The main effect of ΔE_g is to shift the peak of the gain and spontaneous emission spectra toward longer wavelengths.

The Fermi-Dirac distributions in the CB and VB are given by [6,7]:

$$f_c(v) = \left\{ \exp\left(\frac{E_a - E_{fc}}{kT} \right) + 1 \right\}^{-1} \qquad \qquad \ldots \quad (5)$$

$$f_v(v) = \left\{ \exp\left(\frac{E_b - E_{fv}}{kT} \right) + 1 \right\}^{-1} \qquad \qquad \ldots \quad (6)$$

where

$$E_a = \left(hv - E_g(n) \right) \frac{m_{hh}}{m_e + m_{hh}} \qquad \qquad \ldots \quad (7)$$

$$E_b = -\left(hv - E_g(n) \right) \frac{m_e}{m_e + m_{hh}} \qquad \qquad \ldots \quad (8)$$

T is absolute temperature and k the Boltzmann constant. E_{fc} is the quasi-Fermi level of the CB relative to the bottom of the band. E_{fv} is the quasi-Fermi level of the VB relative to the top of the band. They can be estimated using the Nilsson approximation [9]:

$$E_{fc} = \left\{ \ln \delta + \delta \left[64 + 0.05524\delta \left(64 + \sqrt{\delta} \right) \right]^{-1/4} \right\} kT \qquad \ldots \quad (9)$$

$$E_{fv} = -\left\{ \ln \varepsilon + \varepsilon \left[64 + 0.05524\varepsilon \left(64 + \sqrt{\varepsilon} \right) \right]^{-1/4} \right\} kT \qquad \ldots \quad (10)$$

Where

$$\delta = \frac{n}{n_c} \quad and \quad \varepsilon = \frac{p}{n_v} \qquad \qquad \ldots \quad (11)$$

p is the VB hole density. At the carrier density levels usually present in SOAs, p is equal to n. n_c and n_v are constants given by[6]:

$$n_c = 2 \left(\frac{m_e kT}{2\pi\hbar^2} \right)^{3/2} \quad ; n_v = 2 \left(\frac{m_{dh} kT}{2\pi\hbar^2} \right)^{3/2} \qquad \qquad \ldots \quad (12)$$

where

$$m_{dh} = (m_{hh}^{3/2} + m_{lh}^{3/2})^{2/3} \qquad \qquad \ldots \quad (13)$$

m_{lh} is the effective mass of a light hole in the VB.

Finally the noise figure F found from the traveling wave equation is given by [8]:

$$F = \frac{1}{g_m} + \frac{2\sigma_{ASE}}{hvg_m} \qquad \qquad \ldots \quad (14)$$

where the Amplified spontaneous emission spectral density (σ_{ASE}) is given by the equation:

$$\sigma_{ASE} = n_{sp}v(g_m - 1) \qquad \qquad ... \qquad (15)$$

σ_{ASE} is the amplified spontaneous emission that can be established when the pumping signal is applied to SOA.

For the simulation of suggested SOA, the following table presents the typical value of the SOA parameters.

Table I: SOA Geometrical and Material Parameters [6]

Symbol	Parameter	Value
y	Molar fraction of Arsenide in the active region	0.8
K_g	Bandgap shrinkage coefficient	0.9×10^{-10} eVm
n_1	InGaAsP active region refractive index	3.22
a	Bandgap energy quadratic coefficient	1.35
B	Bandgap energy quadratic coefficient	-0.775
C	Bandgap energy quadratic coefficient	0.149
m_e	Effective mass of electron in the CB	4.1×10^{-32} kg
m_{hh}	Effective mass of heavy hole in the VB	4.19×10^{-31} kg
m_{hl}	Effective mass of light hole in the VB	5.06×10^{-32} kg
n_{sp}	Carrier spontaneous density	1.5
f	Baseband frequency.	50 GHz

The suggested device of the SOA, is shown in Figure (1) [10].

Figure (2) below summarizes the development outlined above. Starting with the noise figure definition, the specification of noise as intensity noise or equivalently photocurrent noise in an ideal receiver leads to the general noise figure. This general noise figureis valid for either optical domain or electrical domain measurements of the noise figure. At this point, the path for optical measurements diverges from the path for electrical measurements. On the optical measurement path (to the left), the signal-

Figure (1): The block diagram of suggested SOA

spontaneous beat noise figureis easily characterized by measurement of the ASE density, ASE, and signal gain. Along the optoelectronic electrical measurement path (to the right), the noise figureis measured using electrical measurements of excess noise (Se), the shot-noise density due to the detected signal power Pin (Sshot) and photodetector quantum efficiency(η)[8].
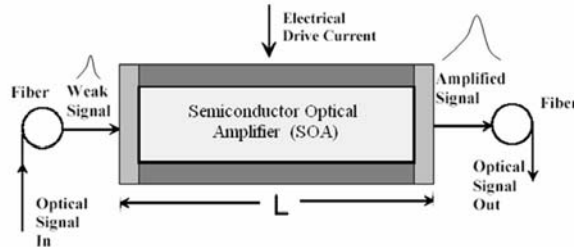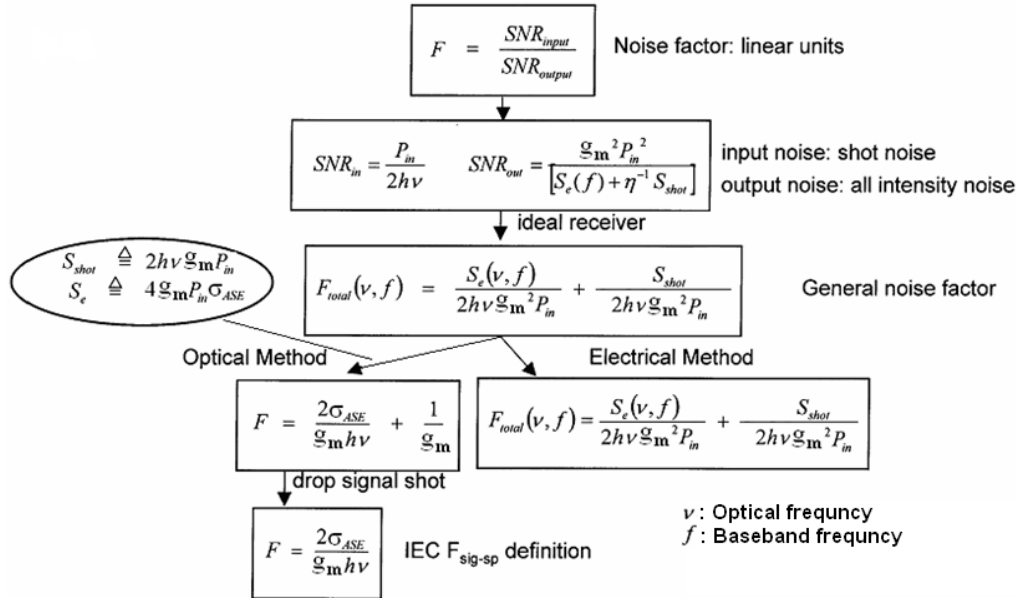
Figure (2): The optical and electrical methods of optical noise figure measurement share the same general noise factor.

III. RESULTS AND DISCUSSION

In order to calculate the noise and the noise figure of SOA, the material gain of the SOA has to be estimated for different mole fractions (y). Figure (3) shows the dependence of the material gain on the wavelength of different values of the mole fraction (y). As can be seen from the figure, the gain reaches its maximum value at definite wavelength. The material gain coefficient of $InGaAs_yP_{1-y}$ semiconductor optical amplifier according to equation(1) is wavelength dependent and mole fraction. The material gain coefficient of SOA is remarkably affected by the mole fraction through the :

1- The variation of energy gap (c.f. eqn.(3)) .
2- The variation of active region refractive index.
3- Qusi_Fermi level separation.

Figure (3): Gain of SOA plotted as a function of wavelength. The device temperature is taken as 300K, at constant pumping current equals 30 mA.

All the factors mention in the above equation were kept constant provided that temperature was maintained stable in order to eliminate the energy gap dependence on temperature. The output photon will emerge when the gain exceeds the loss at a photon energy equal to or greater than $E_g(n)$ as shown in the last term of the equation that is $(h\upsilon - E_g(n))$ and reaches its maximum value depending on impurity added to the semiconductor as given by quasi_Fermi level. This peak value of the gain shifts toward a higher wavelength when the mole fraction is increased.

Also, the variation of gain peak value with the mole fraction is not a linear dependence. In this variation it is very critical for developing a certain SOA for a specified wavelength operation. The gain is often approximated by a polynomial that is a function of photon wavelength and carrier density to carry out good and fast computations [6]. The amount of injected current is fixed at 30 mA.

To study the effect of injected carrier on the material gain of SOA, another simulation is performed but at a constant value of mole fraction (y = 0.8). The gain is calculated for a specified value of injected current of a function of wavelength and then the procedure is repeated again for another current value as shown in figure (4). It is clear from the plot that the gain increase with current is small at a definite wavelength and the peak shift is also negligible. Injected current (a carriers) on the SOA performance is not very crucial as the current is reached its allowed value for gain producing overcome the internal loss. This gain is linear dependence on carrier above the threshold value.
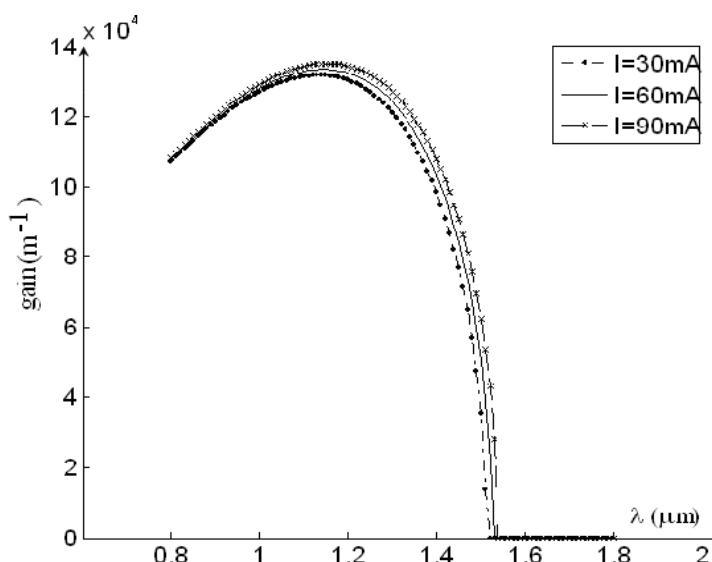

Figure (4): Gain of SOA plotted as a function of wavelength. The device temperature I taken as 300K, at constant y equals 0.8.

In order to discuss the small dependence of gain (g_m) on injected current, referring to equation(2) and (4), we can see that the energy gap depended on the number of injected carrier(n) is very small $(n^{1/3})$.

The goal of this estimation is to find the noise figure of the studied SOA. To achieve this goal, the SOA parameters were listed in Table 1 for this calculation. These typical values were used in the Matlab simulation after gain calculation depending on both the wavelength and current. Then the noise figure can then be easily estimated. A noise figure is plotted for different values of the mole fraction as a function of wavelength. The SOA operation in this calculation is for 1.55 µm.

The noise figure as a minimum value at this wavelength is shown in Figure (5). Besides, the mole fraction dependence (the optimum value of y is 0.8) on the noise figure has many sharp increases at some wavelengths, predicting these wavelengths were not applicable for 3R (reshaping-retiming-retransmission) [9]. Noise figure of $InGaAs_yP_{1-y}$ semiconductor optical amplifier of 1.3μm had shown a pronounced peaks other than the operating wavelength of SOA, noise figure given equation (14) is intrinsically dependent on the gain material (g_m) and the factor (σ_{ASE}) which can be related to the parameters of the SOA. Noise figure which known as (SNR_{input}/SNR_{output}) is more or less has its effect on the input/output related factor of the
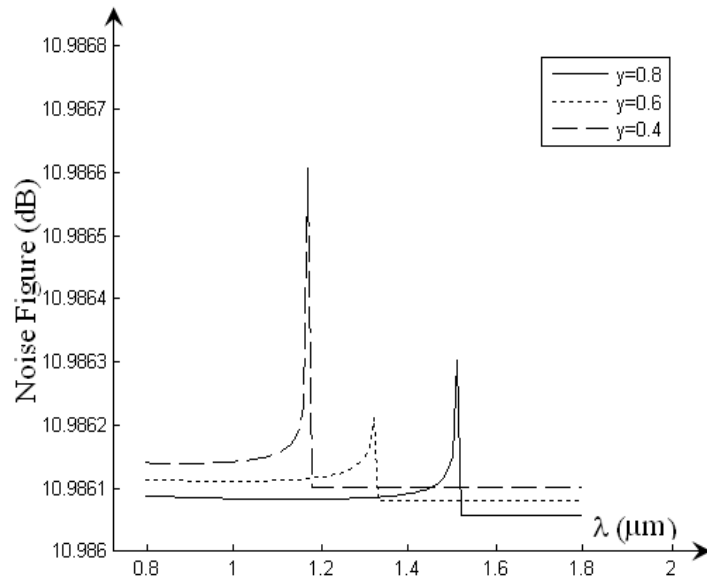

Figure (5): Noise figure of SOA plotted as a function of wavelength. The device temperature is taken as 300K, at constant pumping current equals 30 mA.

SOA. The pronounced peaks of the noise figure had been shifted to longer wavelength when the mole fraction was increased beyond the operating wavelength at an optimum value y = 0.8.

V. CONCLUSIONS

The SOA of InGaAsP (λ=1.55 μm) has a very crucial dependence on the mole fraction and that is to be taken in to consideration in developing procedure. Current of SOA operation is not very important as the SOA has reached its threshold value. Noise figure of the SOA under investigation should have a very minimum value at the operating wavelength.

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