1985年1月 通 信 学 报 Vol.6 № 1.
第6卷第1期 JOURNAL OF CHINA INSTITUTE OF COMMUNICATIONS Jan. 1985

非均匀光增益层所产生的噪声

J. 阿诺德
(法国蒙特利列尔大学)

[提要] 由表面发射激光放大器和检测器组成的光接收器的噪声因任何增益的非均匀性而增加。如果用$G(x,y)$表示在点x，y处表面发射激光放大器的功率增益；用$I(x,y)$表示入射光强，则噪声增强因子K'等于$\int G^2I\int I\Big/\left(\int GI\right)^2\geqslant 1$，其中积分对$x$，$y$从$-\infty$到$+\infty$区域进行。最佳值1仅当$G=$常数时得到。

Noise Generated by Slabs with Nonuniform Optical Gain

J. Arnaud*

Abstract: *The noise of an optical receiver consisting of a surface emitting laser amplifier and a detector is enhanced by any lack of gain uniformity. If $G(x, y)$ denotes the power gain of the surface emitting laser amplifier at a point x, y and $I(x, y)$ the incident optical beam intensity, the noise-enhancement factor K' is equal to $\int G^2 I \int I/(\int GI)^2 \geqslant 1$ where the integrals are over x, y from $-\infty$ to $+\infty$. The best value, unity, is reached only if G=constant.*

1. INTRODUCTION

In coherent optical communication systems it may be advisable to amplify optical signals before detecting them[1,2]. In that way, the detector noise may be overcome. Laser amplifiers, however, generate incoherent optical power by spontaneous emission. This optical power in turn mixes with the optical signal and generates a noise power (N) at the detector output. It can be shown that when the optical amplifier gain is large compared with unity, the noise to signal ratio is given by the simple formula

$$N/S=4\,hf/P_0 \tag{1}$$

at the detector output, independently of the detector noise. In this expression, S is the square of the signal detector current, while N is the mean square of the detector current fluctuations per unit bandwidth. hf represents the photon energy and P_0 the received optical power. Equation (1) rests on the following assumptions:

-The population inversion is complete

-The quantum efficiency of the detector is not small compared with unity

-The shot noise and the self-beating of the spontaneously emitted light are negligible. This is the case when the optical gain is large, the number of amplified modes is not very large, and the detector bandwidth is not very small compared with the optical linewidth.

Finally, the gain is supposed to be spatially uniform. The purpose of the present paper is to discuss this last assumption. To that effect, we consider a thin sheet of material with gain, and show that if the gain varies significantly within the area over which the incident beam has significant inten-

* Equipe de Microoptoélectronique de Montpellier Universite des Sciences et Techniques du Languedos Place E. Bataillon, F. 34060 Montpellier Cedex, FRANCE.

sity, the right-hand-side of Eq. (1) should be multiplied by a factor $K' \geqslant 1$. The configuration presently investigated is represented in Fig. 1, where the incident beam intersects at right angle an amplifying thin sheet. Iga[2] has shown that such a configuration provides significant gain even at room temperature. In the case where the optical wave propagates along the slab with gain, rather than perpendicular to it, a spontaneous emission enhancement factor K was first proposed by Petermann[4], and modified by Arnaud[5] and Coste et al.[6] We are presently discussing quite a different geometric configuration.

2. EXPRESSION OF THE SIGNAL POWER S

Let $\psi(x, 0)$ denote the incident optical field (plane $z=0$ of Fig. 1) and $\psi(x, L)$ the output field. These fields are supposed to be normalized in such a way that the power density is $|\psi|^2$. The power optical gain G_0 is then evidently

$$G_0=\iint|\psi(x, L)|^2 dx dy \Big/ \iint|\psi(x, 0)|^2 dx dy \tag{2}$$

The medium, $0 \leqslant z \leqslant L$, may be characterized by a complex index of refraction n

$$n \equiv n_r + i n_i; \quad k \equiv (\omega/c) n; \quad k_i = (\omega/c) n_i = -g \tag{3}$$

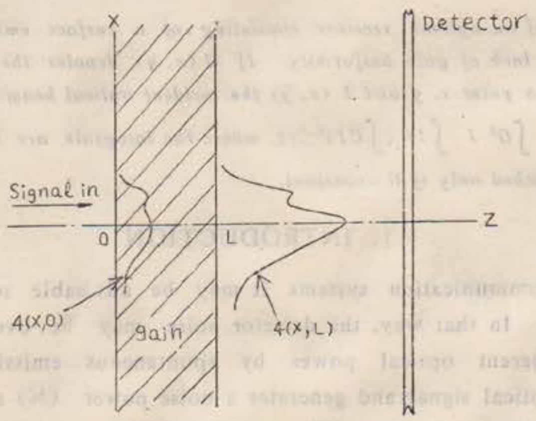

Fig. 1 An optical beam (signal in) is amplified as it crosses a slab with gain. The amplified beam field $\psi(x, L)$ beats with the spontaneously generated field to generate a noise current at the detector

where n_r, n_i denote the real and imaginary parts of n, $\omega=2\pi f$, and g may be called the medium gain. This gain parameter $g(x, y, z)$ is assumed to vary slowly with x and y, so that diffraction effects can be neglected over the short propagation length L. Yet, g may vary significantly over the incident optical beam radius. We thus have

$$\psi(x, y, z)=\psi(x, y, 0) \exp\left[i\int_0^z (\omega/c)\, n(x, y, z)\, dz\right] \tag{4}$$

so that, from Eqs. (2) and (3), the power gain G_0 is

$$G_0=\iint I(x, y)\, G(x, y)\, dx dy / P_0, \tag{5}$$

$$I(x, y)=|\psi(x, y, 0)|^2$$

$$G(x, y)=\exp\left[\int_0^z g(x, y, z)\, dz\right]$$

$$P_0=\iint I(x, y)\, dx dy$$

Now, if the detector quantum efficiency is η each incident photon gives η electrons, so that the signal power S is

$$S \equiv i_0^2=\left(\frac{\eta e}{hf} G_0 P_0\right)^2 \tag{6}$$

3. NOISE POWER

As indicated in the introduction we shall consider only the beat between the optical power spontaneously emitted in the laser amplifier and the optical signal, the other noise terms being negligible in the limit where $G_0 \to \infty$.

The noise power at the detector output (mean square of the current fluctuations) is

$$N=4(\eta e/hf)^2 \iiint_{slab} \left|\iint \psi^*(x, y, L)\, \psi_{sp}(x, y, L; x_0, y_0, z_0)\, dx dy\right|^2 \tag{7}$$

where $\psi(x, y, L)$ denotes the signal field at the detector plane and ψ_{sp} the field spontaneously emitted by a small volume $dx_0\, dy_0\, dz_0$ located around x_0, y_0, z_0 within the slab, and a spectral range unity. Nonoverlapping volumes of the active medium generate fields with random phases so that only powers add up. The surface integral in Eq. (7) is over the detector plane (x, y from $-\infty$ to $+\infty$), while the triple integral is over the slab volume (x_0, y_0 from $-\infty$ to $+\infty$ and z_0 from 0 to L);

The field spontaneously emitted at z_0 by a volume centered around z_0 is represented by a δ-function in x and y

$$\psi_{sp}(x, y, z_0; x_0, y_0, z_0)=[2hfg(x_0, y_0, z_0)\, dx_0\, dy_0\, dz_0]^{1/2}\, \delta(x-x_0)\, \delta(y-y_0) \tag{8}$$

Note that the medium gain g which represents stimulated emission in Eq. (5) also enters in the expression, Eq. (8), of the spontaneously emitted field. This fact expresses the well-known Einsteins's relation between the A and B coefficients[1]. Because diffraction is neglected over the thim length L, the field created at $z=L$ by the field distribution at z_0 given in Eq. (8) remains in the form of a δ-function, and we need only take into account the amplification from $z=z_0$ to $z=L$

$$\psi_{sp}(x, y, L; x_0, y_0, z_0)=\psi_{sp}(x, y, z_0; x_0, y_0, z_0) \times \exp\left[i\int_{z_0}^L (\omega/c)\, n(x, y, z)\, dz\right] \tag{9}$$

Equation (9) also expresses a phase change from z_0 to L which, however, does not remain in the final expression for N.

When these expressions, Eqs (8), (9), are introduced into Eq. (7) we obtain for these noise power spectral density

$$N=(\eta e/hf)^2 \iiint 2hf\, g(x_0, y_0, z_0)\, dx_0\, dy_0\, dz_0 \times \left|\iint \psi^*(x, y, 0)\, e^{-i\int_0^L k^*(x, y, z)\, dz}\, \delta(x-x_0)\, \delta(y-y_0) \times e^{i\int_{z_0}^L k(x, y, z)\, dz}\, dx dy\right|^2 \tag{10}$$

After integration over x, y, we notice that

$$\left|e^{-i\int_0^L k^*(x_0, y_0, z)\, dz}\right|^2=G(x_0, y_0) \tag{11}$$

and

$$\int_0^L 2g(x_0, y_0, z_0) \exp\left[\int_{z_0}^L 2g(x_0, y_0, z)\, dz\right] dz_0=G(x_0, y_0)-1 \tag{12}$$

We thus arrive at the simple expression for the baseband noise-to-signal ratio

$$N/S=4hf\iint G(G-1)\, I \Big/ \left(\iint GI\right)^2 \tag{13}$$

where G stands for $G(x_0, y_0)$, I for $I(x_0, y_0)$ and the integrations are over x_0, y_0 from $-\infty$ to

$+\infty$. If the gain of the amplifying slab is uniform, that is, if G is independent of x and y, and large compared with unity, we find from Eq. (13): $N/S=4hf/P_0$ as stated earlier in Eq. (1).

We are thus led to define in the general case of nonuniform G a noise enhancement factor

$$K'=(N/S)(P_0/4hf)=\int\int G^2 I \int\int I \Big/ \left(\int\int GI\right)^2 \tag{14}$$

where we have assumed here again that $G\gg 1$. This factor is called K' to avoid a confusion with Petermann's K-factor[4] which has a different significance. To show that the right-hand-side of Eq. (14) is always larger or equal to unity notice first that

$$\left[\int\int I\left[G-\int\int (GI)\Big/\int\int I\right]^2\geqslant 0 \tag{15}$$

because the integrand is always positive (G real and I real positive). If we perform the integration in Eq. (15), the announced result follows readily. The best signal-to-noise ratio $K'=1$ is thus achieved when the gain G is a constant over the incident beam area.

As an example of application of Eq. (14), let us assume that the incident beam has uniform intensity over a circular cross-section of radius ρ, while the active slab has gain over a concentric area of radius $\rho/2$ only. A straightforward integration shows that the noise enhancement factor is

$$K'=4 \tag{16}$$

4. CONCLUSION

We have shown on theoretical grounds that when an optical beam is amplified by a thin active slab, any lack of uniformity of the slab gain enhances the noise which contaminates the amplified signal. In such configurations (e. g., in surface emitting semiconductor laser amplifiers[3]) it is therefore important to ensure pumping uniformity.

REFERENCES

[1] A. Yariv, Introduction to Optical Electronics, Holt, Rinehart and Wireston, N. Y. 1976, Chapter 10.

[2] J. C. Simon, J. of Opt. Comm. 4, 1983, No. 2, p. 51.

[3] S. Ishikawa, S. Ohkouchi and K. Iga, in Conf. on Lasers and Electro-optics, June 19—22, 1984, Anaheim conv, center.

[4] K. Petermann IEEE J. of Q. Elec. QE. 15, No. 7, July 79, p. 566.

[5] J. Arnaud, Electr. Letters 19, No. 17, 18 th Aug. 83, p. 688.

[6] F. Coste, J. Fesgnet and J. Arnaud (unpublished).

中国通信学会1985年主要学术活动安排

项　目　名　称	时间	地点	项　目　名　称	时间	地点
第三次邮政学术年会	6月	西安	第三次电信学术年会	3季	待定
沿海开放城市通信现代化(电信)研讨会	4月	青岛	光缆技术交流会	3季	成都
通信企业经营管理学术讨论会	待定	待定	传真及办公室自动化专题讨论会	10月	兴安
省内微波通信技术讨论会	二季	西安	公用数据网开发专题讨论会	待定	待定
局部数据网专题讨论会	待定	待定	通信与信息理论学术会议	3—4季	待定
中小城市、农村电话及电话机学术交流会	9月	无锡	程控技术在通信设备制造方面应用交流会	10月	上海
光通信半导体器件学术讨论会	7月	长春	小系统光通信推广应用交流会	10月	武汉
无线通信网(局部网)学术讨论会	4季	安徽	汉字终端在电报中的应用讨论会	3季	待定
通信电源学术讨论会	3季	待定	综合业务数字网(ISDN)学术讨论会	3季	待定
经济特区及沿海开放城市通信现代化学术讨论会	4季	待定	通信设备制造热处理技术交流会	6月	眉山