Operation Stability of Semiconductor Lasers In Optical Fiber Communication Systems

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Abstract. The paper reports an analysis of the dynamics and operation stability of pumping semiconductor lasers of optical fiber amplifiers in optical communication systems. The parameters of the amplifier system that correspond to stable operation and low intensity noise are explored. The study is based on a time-delay model of the rate equations of the photon number, optical phase and the injected electron number. The analyses are performed in terms of the instantaneous fluctuations of the laser intensity, the corresponding bifurcation diagram and phase portraits, and the relative intensity noise. The frequency spectra of the intensity noise under strong feedback are characterized. The results indicate that the laser stability improves when the length of the external cavity formed between the laser and a fiber grating decreases where the laser operates almost in either pulsation or continuous wave. The operation becomes almost chaotic interrupted by narrow regions of continuous wave in the extreme of long external cavities, which degrades the laser stability.

1. Introduction

Optical fiber amplifiers have been recently utilized to compensate weakness of the transmitted signal down optical fibers and hence to increase the transmission distance in optical fiber communication systems (Agrawal, 2003). In such systems, semiconductors lasers consisting with external fiber cavities terminated with fiber gratings (FGs), as shown in Fig. 1, have been popularly used as exciting sources for fiber amplifiers (rare-earth-element doped fibers). The external fiber cavity is introduced to increase the lasing power over both the internal (the solitary laser) and the external fiber cavities. The FG is introduced to lock the lasing frequency to a single frequency of the external cavity resonances or to a limited range of frequencies. The pumping semiconductor lasers are designed with an antireflection-coated front facet. Therefore, these lasers suffer from very strong external optical feedback (OFB) due to reflection of the laser light by the FG and re-injection into the laser cavity (Mokai & Otsuka, 1985). Recent investigations of the operation characteristics of such lasers have indicated that the device may operate in continuous wave (CW) or pulsation (periodic or quasi-periodic) depending on the lasing conditions and the system configuration (Abdulkhmann et al., 2003). One drawback of the optical fiber amplifier is that it amplifies both the signal and the noise induced upon propagation of the lightwave down the fibers. Stabilizing the operation of the pumping
laser and suppressing the corresponding intensity noise to its lowest quantum level are necessary to improve the performance of the optical amplifier systems. Therefore, characterization of the intensity noise is prerequisite in this regard.

Fig. (1). Scheme of a pumping laser diode in an optical fiber amplifier system.

Recently, a new model of OFB in semiconductor laser diodes has been reported which is exceptionally applicable to an arbitrary strength of the OFB (Abdulrhamman et al., 2003). In this paper, we apply such a model to analyze the dynamics, intensity noise, and operation stability of pumping lasers in fiber amplifier systems. We are aimed at exploring the OFB parameters that correspond to stable operation and low noise, namely, the reflectivity of the FG and its distance to the pumping laser. The analyses are made in terms of the instantaneous fluctuations of the light intensity, the corresponding bifurcation diagram and phase portrait, and the spectrum of the relative intensity noise (RIN).

The paper is structured as follows. The theoretical model of laser dynamics and noise is given in the next section. Section 3 presents the procedures of applying the proposed model in numerical calculations. In section 4, we demonstrate the simulation results of laser dynamics and noise under OFB. The conclusions are given in section 5.

2. Theoretical Model

The proposed model of laser operation under OFB in a fiber amplifier system is schematically illustrated in Fig. 2. The light emitted from the laser front facet at a time \( t \) travels for a time of \( \tau = 2nL_F/c \) in the external cavity formed between the laser front facet of reflectivity \( R_L \) and the FG of reflectivity \( R_E \), with \( L_F \) and \( n_F \) as the length and refractive index of the external cavity, and \( c \) as the speed of light in vacuum. The light then travels back to the cavity and re-injects into the laser cavity through the front facet. That is, at a time \( t \) and at the front facet, the photon number \( S(t) \) inside the cavity \( S(t) \) is influenced by the time-delayed value \( S(t-\tau) \) in the external cavity. Such phenomenon is described by the following rate equations of the photon number \( S(t) \), optical phase \( \theta(t) \) and injected electron number \( N(t) \) (Abdulrhamman et al., 2003):

\[
\frac{dS}{dt} = \left( A - BS - G_{in} + \frac{c}{n_L L_{in}} \ln |U| \right) S + \frac{a g_F}{V} N + F_S(t), \quad (1)
\]

\[
\frac{d\theta}{dt} = \frac{1}{2} \left[ \frac{a a g_F}{V} \left( N - N_L \right) + \frac{c}{n_L L_{in}} \varphi \right] F_S(t) + F_\theta(t). \quad (2)
\]

\[
\frac{dN}{dt} = -AS - N \frac{1}{\tau_e} + e + F_S(t), \quad (3)
\]
where $A$ and $B$ are linear and nonlinear coefficients of optical gain $G_{Dx}$, respectively. They are determined in terms of the number of injected electrons $N$ as (Ahmed & Yamada, 1998),

$$A = \frac{\sigma_0}{V} \left( N - N_e \right). \quad (4)$$

$$B = \frac{9\pi e}{2\varepsilon_0 n_e^2 \hbar \lambda} \left( \frac{\varepsilon R_{em}}{V} \right)^2 q |R_{\infty}|^2 \left( N - N_e \right). \quad (5)$$

The parameters in the above equations are defined as follows. $\alpha$ is a tangential coefficient of $A$, $\xi$ is the field confinement factor in the active region, $V$, $L_D$, and $n_D$ are the volume, length and spatially-averaged refractive index of the active region, respectively, $N_e$ is the electron number at transparency, $N_i$ is an electron number characterizing the nonlinear gain coefficient, $\bar{N}$ is a time-averaged value of $N$, $\lambda$ is the emission wavelength, $|R_{\infty}|^2$ is the squared absolute value of the dipole moment, $G_{th}$ is the threshold gain in the solitary laser, $I$ is the injection current, $\tau$ is the lifetime of electrons due to spontaneous emission, $\tau_a$ is the intraband relaxation time, and $e$ is the electron charge. The term $\alpha N/V$ in Eq. (1) indicates the rate of inclusion of the spontaneous emission into the lasing mode.

The OFB is counted in terms of the function $U$ and its argument $\varphi$ which are defined in terms of the delay round-trip time $\tau$ as (Abdulrhmaan et al., 2003):

$$U = 1 - K_c \exp \left[ -j \varphi \right] \left[ \frac{S(t - \tau)}{S(t)} \right] \exp \left\{ j \left( \theta(t - \tau) - \theta(t) \right) \right\}, \quad (6)$$

$$= |U| \exp \left\{ -j \varphi \right\}$$

$\varphi$ represents the phase difference between the delayed injected field and the reflected field to the laser cavity at the front facet,

$$\psi = \omega \tau + \varphi_f + \varphi_e,$$

where $\varphi_f$ and $\varphi_e$ are the phase changes of the field at the front facet and the fiber grating, respectively, and $\omega \tau$ is the phase delay during each round trip in the external cavity. The feedback coefficient $K_{fe}$ measures the strength of OFB and is determined by the ratio of the external reflectivity $R_e$ to the front-facet reflectivity $R_f$ as,

$$K_{fe} = (1 - R_f) \left( \frac{n R_e}{R_f} \right), \quad (8)$$
where \( \eta \) is the coupling ratio of the externally reflected light into the laser cavity. The argument \( \varphi \) of the feedback function \( U \) is obviously given by:

\[
\varphi = - \tan^{-1} \left( \frac{\text{Im}[U]}{\text{Re}[U]} \right) + m \pi,
\]

where \( m \) is an integer. Determining the value of \( \varphi \) in the two-dimensional space (Re\([U]\), Im\([U]\)) depends on both the signs and magnitudes of Re\([U]\) and Im\([U]\).

The terms \( F_d(t) \), \( F_b(t) \) and \( F_N(t) \) are Langevin noise sources of a Gaussian type with zero means, and satisfy the following cross-correlations (Ahmed et al., 2001):

\[
F_d(t) F_b(t') = V_{ab} \delta(t - t'),
\]

where \( a \) and \( b \) stand for any of \( S, N \) or \( \theta \). These random terms are added to the rate equations to account for the quantum noises associated with inclusion of the spontaneous emission and recombination processes of charge carriers (Ahmed et al., 2001). The variances \( V_{ab} \) are determined from the steady-state solutions \( \bar{S} \) and \( \bar{N} \) of Eqs. (1)-(3).

The noise content of the output fluctuations is determined in terms of the RIN. The RIN is calculated from the fluctuations \( \delta S(t) = S(t) - \bar{S} \) of \( S(t) \) via the equation (Ahmed et al. 2001):

\[
\text{RIN} = \frac{1}{\bar{S}^2} \left( \frac{1}{T} \int_0^T \left\{ \delta S(t)e^{j2\pi \Omega t} \right\}^2 dt \right),
\]

where \( \Omega \) is the Fourier frequency and \( \bar{S} \) is the time-average value of \( S(t) \).

### 3. Numerical Calculations and Results

#### 3.1. Procedures of Calculations

In the present calculations, typical values of the parameters of both 980 nm InGaAs laser diodes and the geometry of fiber amplifier systems are employed. These values are listed in Table 1. The rate equations (1)-(3) are solved numerically by means of the fourth-order Runge-Kutta method. The time step of integration is set as short as \( \Delta t = 5 \text{ps} \) to guarantee fine resolution of the OFB-induced dynamics. This small time step \( \Delta t \) corresponds to a cut-off frequency much higher than the external-cavity mode-separation frequency \( f_{cs} = 1/\tau \). The operation state is examined in the period \( t = 8-10 \mu s \) during which the operation state is fixed. The integration is first made without OFB (case of the solitary laser) from time \( t=0 \) until the round trip time \( \tau \). The calculated values of \( S(t,0 \rightarrow \tau) \) and \( \theta(t,0 \rightarrow \tau) \) are then stored for use as time delayed values \( S(t - \tau) \) and \( \theta(t - \tau) \) for further integration of the rate equations including OFB terms. The phase difference \( \psi \) is arbitrary and is set as zero in the present calculations. The spectrum of the RIN is computed directly from the obtained instantaneous values of \( \delta S(t) = S(t) - \bar{S} \) by applying the fast Fourier transform (FFT) to integrate the discrete version of Eq. (11) as (Ahmed, 2003):

\[
\text{RIN} = \frac{1}{\bar{S}^2} \frac{\Delta t^2}{T} \left\| \text{FFT}[\delta S(t)] \right\|^2,
\]
Table 1. Typical Values of Parameters of AlGaAs Lasers and Geometry of Optical-Fiber Amplifier Systems.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_r )</td>
<td>Distance of laser diode to optical disc</td>
<td>varies</td>
<td>cm</td>
</tr>
<tr>
<td>( n_f )</td>
<td>Refractive index of the fiber</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>( a )</td>
<td>Tangential parameter of linear gain</td>
<td>( 2.21 \times 10^{-12} )</td>
<td>m/s</td>
</tr>
<tr>
<td>( N_{g2} )</td>
<td>Electron number at transparency</td>
<td>( 4.08 \times 10^{18} )</td>
<td></td>
</tr>
<tr>
<td>( R_0 )</td>
<td>Square value of the dipole moment</td>
<td>( 2.8 \times 10^{-17} )</td>
<td>C/cm²</td>
</tr>
<tr>
<td>( N_e )</td>
<td>Value of the electron number</td>
<td>( 1.53 \times 10^{18} )</td>
<td></td>
</tr>
<tr>
<td>( \tau_{e0} )</td>
<td>Characterizing the nonlinear gain</td>
<td>0.1</td>
<td>ps</td>
</tr>
<tr>
<td>( \tau_e )</td>
<td>Electron lifetime</td>
<td>2.7 ns</td>
<td></td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Linewidth enhancement factor</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>( n_{uo} )</td>
<td>Refractive index of active region</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>( L_d )</td>
<td>Length of the active region</td>
<td>800μm</td>
<td></td>
</tr>
<tr>
<td>( V )</td>
<td>Volume of the active region</td>
<td>400 μm³</td>
<td></td>
</tr>
<tr>
<td>( \xi )</td>
<td>Field confinement factor</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>( R_f )</td>
<td>Reflectivity at front facet</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>( R_b )</td>
<td>Reflectivity at back facet</td>
<td>0.98</td>
<td></td>
</tr>
</tbody>
</table>

In order to perform the above calculations, discrete generations of the noise sources at each instant are necessary. Theses processes require enough care in order to satisfy the cross-correlations of the noise source \( F_s(t_j) \) with \( F_s(t_k) \) and \( F_\theta(t_j) \) at each time \( t_k \), which originate in the cross-correlation between \( S \) and \( N \) during the lasing action. In this paper, we follow the self-consistent technique proposed by Ahmed et al. (Ahmed et al., 2001) to adopt such generation processes. The obtained forms of the noise sources are:

\[
F_s(t_r) = \sqrt{\frac{V_{ss}(t_r)}{\Delta t}} g_s
\]

\[
F_\theta(t_r) = \frac{1}{S(t_r-1)+1} \sqrt{\frac{V_{ss}(t_r)}{\Delta t}} g_\theta
\]

\[
F_N(t_r) = \sqrt{\frac{V_{ss}(t_r) + 2k_s(t_r) V_{ss}(t_r)}{\Delta t}} g_N - k_s(t_r) \{ F_s(t_r) + 2[S(t_r-1)+1]F_\theta(t_r) \}
\]

with

\[
V_{ss}(t_r) = 2a\xi \left[ S(t_r-1) + 1 \right] N(t_r-1)
\]

\[
V_{ss}(t_r) = 2 \left[ \frac{1}{\tau_e} + \frac{a\xi}{V} S(t_r-1) \right] N(t_r-1)
\]

\[
V_{ss}(t_r) = -\frac{a\xi}{V} \left[ S(t_r-1) + 1 \right] + N_s S(t_r-1)
\]

\[
k_s(t_r) = -\frac{V_{ss}(t_r)}{V_{ss}(t_r)}
\]

In the above equations, \( g_s, g_\theta, \) and \( g_N \) are three independent Gaussian random numbers with means of zero and variances of unity. They are obtained at each integration step by applying the Box-Mueller approximation (Press et al., 1992) to a set of three uniformly distributed independent random numbers generated by the computer.
4. Results and Discussion

4.1. Time variation of laser intensity and spectrum of RIN

Examples of the simulation results of laser output and noise in the strong OFB regime are given in Fig. 3 when the injection current is well above the threshold, \( I = 5I_{\text{th}} \) with \( I_{\text{th}} \) as the threshold current in the solitary laser. Figures 3(a)-(c) plot the temporal trajectories of the photon number \( S(t) \) when \( K_{e} = 1.1, 3.9 \) and 4.4, respectively. Figures 3(d)-(f) plot the corresponding phase portraits \( [S(t) \text{ versus } N(t)] \), and Figs. 3(g)-(i) plot the corresponding spectra of the RIN. Figure 3(a) shows that the emitted photon number \( S(t) \) fluctuates around its average value \( \bar{S} \). The amplitude of the fluctuations is comparable to that of the solitary laser. That is, the laser operates in CW. Figure 3(d) indicates almost a point attractor of the phase portrait. The corresponding RIN spectrum shown in Fig. 3(g) exhibits low-frequency components little higher than the components of the RIN of the solitary laser. The spectrum has peaks around the sub-harmonic \( 1/2 \) of the compound-cavity mode-separation frequency \( f_r = c/(2n_0 d + n_m L_e) \approx 4 \) GHz and its higher harmonics. This indicates that the fluctuations of \( S(t) \) have a periodic component with \( f_r/2 \). The peak of the RIN of the solitary laser corresponds to the well-known relaxation oscillation of frequency \( f_r = 4 \) GHz.

![Diagram](image)

Fig. (3). The simulated data of (a)-(e) time variation of the photon number \( S(t) \), (d)-(f) phase portraits, and (g)-(i) RIN spectra when \( K_{e} = 1.1, 3.9 \) and 4.4, respectively.

Figure 3(b) indicates that the laser emits regular pulses when \( K_{e} = 3.9 \), although the device is injected with a DC current. The phase portrait 3(c) indicates an attractor of a single orbit, which characterizes the regular pulsation. However, such an attractor deviates from the perfect case of the limit cycle attractor because the pulses are broadened and have
tails in their lower side. The RIN spectrum in Fig. 3(h) exhibits very high and sharp peak around \( f_c \), and the low-frequency part of the RIN is almost flat (white noise) but is 2.5 orders of magnitude higher than the corresponding level of the solitary laser. This increase of RIN is because of the deviation of the limit attractor from the circular type.

Figure 3(c) shows another type of pulsation induced by the strong OFB (\( K_{ec} = 4.4 \)); the pulsation is period doubling, where the pulses have two distinguished peaks; the frequency of each pulsation is the sub-harmonic \( f_c/2 \), while the fine frequency is \( f_c \) itself. The phase portrait in Fig. 3(f) reflects this result with the double-orbit attractor. The RIN spectrum in Fig. 3(i) exhibits very high and sharp peaks around the sub-harmonic \( f_c/2 \) and its higher harmonics. Although the low frequency part is as high as the case of \( K_{ec} = 3.9 \), it behaves as a \( 1/f \) dependency.

4.2. Effects of OFB and the external cavity length on the laser output

Influence of the OFB on the laser output is discussed in terms of the bifurcation diagram shown in Fig. 4, which is a convenient method for showing the type of route to chaos of the laser (Mork et al., 1992). The diagram is calculated numerically at a constant current of \( S_{th} \), and is constructed by picking up the peak(s) \( S_{peak} \) of the time-varying photon number \( S(t) \) normalized by the corresponding time-average value \( \bar{S} \) at each strength \( K_{ec} \) of OFB. Figure 4(a) plots the obtained diagram when \( L_c = 5 \) cm. For small values of \( K_{ec} \), the laser still operates stably in CW; the figure plots points that represent weak fluctuations of \( S(t) \) around \( \bar{S} \). At a certain value of \( K_{ec} = 0.03 \), the laser output becomes periodic as the relaxation oscillations become undamped. The result is then a single point in the bifurcation diagram (or several adjacent points that represent fluctuation components on the pulses due to inclusion of the Langevin noise sources). At another critical value of \( K_{ec} = 0.07 \), the laser begins a period-doubling route to chaos. Such chaotic operation induces strong instabilities in the laser operation and enhances the laser noise (Ahmed et al., 2004). The chaos disappears abruptly when \( K_{ec} = 0.11 \), giving a way to a region of CW-operation followed by a region of frequency locking in which the output is once again stable and periodic. At \( K_{ec} = 0.31 \) and 2.8, the laser enters also other two regions of pulsing operation interrupted by a window of CW operation. The range of OFB over which the regular pulsation extends decreases and the pulses become almost period-doubling with the increase of \( K_{ec} \). It is interesting to note that the locking frequency of each pulsing cycle increases with the increase of \( K_{ec} \), starting with the laser relaxation frequency \( f_c \) in the first cycle, passing through the compound-cavity mode-frequency separation \( f_c \), and ending with the external-cavity mode-frequency separation \( f_c \).

We also analyze the effect of the length of the external cavity \( L_c \) on the laser cavity. Figures 4(b)-(d) plot the diagrams for longer cavities \( L_c = 10, 30 \), and 100 cm, respectively. When \( L_c = 10 \) cm, the figure shows two chaos cycles separated by a CW region. The laser still exhibits a region of frequency locking in the strong OFB regime but at \( K_{ec} \) values larger than the case of \( L_c = 5 \) cm. In the case of \( L_c = 30 \) cm, Fig. 4(c) shows that the chaos cycles become wider. The route-to-chaos of the first cycle is still periodic, whereas it is quasi-periodic in the second cycle. Moreover, the pulses in the frequency locking regime of strong OFB becomes period doubling or tripling, which degrades the laser stability and promotes the RIN level. Figure 4(d) indicates much wider two chaos cycles (i.e., more unstable operation) with both cycles having quasi-period routes-to-chaos. The pulses in the strong OFB regime become more irregular.
Fig. (4). Bifurcation diagrams of the laser photon number $S(t)$ under external cavity of length (a) $L_F=5\text{ cm}$, (b) $L_F=10\text{ cm}$, (c) $L_F=30\text{ cm}$, and (d) $L_F=100\text{ cm}$. The operation is almost pulsing or CW under shorter cavity. The instabilities increase and the operation becomes more chaotic with the increase of $L_F$.

4.3. Effect of OFB on the output power

The power emitted from the fiber grating $P_{x}$, i.e., the pumping power of the fiber amplifier, is an important parameter of the optical fiber amplifier system. The power $P_{x}$ is calculated based on a traveling wave model of the lasing field in the laser and external cavities (Abdulrhammm et al., 2003),
\[ P_x(t) = \frac{\hbar \alpha_r n_x}{2 \alpha_r L n_D} (1 - R_e) \left( 1 - R_f \right) \frac{(1/2) \ln \left( 1/R_e R_f \right) + \ln \left( 1/|U| \right)}{1 + \sqrt{1/\sqrt{R_b} - \sqrt{R_f}} |U| - |U|^2 R_f} X^2 S(t) \] 

(20)

where \( X \) is another OFB function describing transmission of the lasing field in the external cavity, and is given by.

\[ X = 1 + \sqrt{R_b R_f} e^{-i\omega t} \left( \frac{S(t - \tau)}{S(t)} \right) e^{i[\theta(t - \tau) - \theta(t)]} \]

(21)

Figure 5 plots variation of the time-averaged power \( \overline{P}_x \) with the variation of the feedback strength \( K_e \) when \( L_F = 5 \text{ cm} \) and \( J = 5 \text{mA} \). The figure shows that \( \overline{P}_x \) increases monotonically with \( K_e \) until \( K_e \approx 1 \), then it increase rapidly. This result explains the reason why AR-coating and high-reflectivity gratings (i.e., very weak \( R_b \), very strong \( R_g \), and very large \( K_e \)) are desirable in the design of pumping lasers and optical fiber grating systems.

![Graph](image)

**Fig. (5)**. Variation of the power emitted from the FG with the strength \( K_e \) of the OFB. The power increases slowly under low OFB but rapidly under strong OFB.

5. Conclusion

We characterized the influence of OFB on the operation stability and noise of semiconductor lasers in optical fiber communication systems. The study is based on an improved time-delay model. The following conclusions can be drawn.

1- The operation is almost periodic with frequency locking at the compound-cavity modeseparation frequency or the external-cavity mode-separation frequency under strong external optical feedback.

2- When the external cavity is short, the operation is almost stable and is either pulsing or continuous wave. The low-frequency part of the relative intensity noise is lowest under continuous wave. The low-frequency noise is flat when the pulsation is uniform, but decreases as \( 1/f \) when the pulsation is period doubling or tripling.
3. The instabilities increase and the noise level increases with the increase of the length of the external cavity. The operation is almost chaotic separated by narrow regions of continuous wave operation.

Acknowledgements

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References


استقرار عمل ليزر أشباه الموصلات في أنظمة اتصالات الألياف الضوئية

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المستخلص:

يتضمن هذا البحث تحليل ديناميكي واستقرار عمل الليزر المستخدم في صخ أنظمة مكبات الألياف الضوئية، فاعرض اكتشاف مناطق تشغيل الليزر المستقرة التي تميزت بمعدلات مستقرة للإضاءة، وتعتبر هذه الدائرة على نطاق زمني تأخير يمر بالانعكاسات وتغير في الثوثر الضوئي وعند الإلكترونات المحكمة. وتتم التحليلات النظرية في هذا البحث بدلالة الشروط البيئية لانعدام الظروف الضوئية، ولنorum في هذا البحث يصنف عملية التشغيل المستقرة في مناطق التشغيل المستقرة وغير المستقرة، ونستعرض التحليلات النظرية لمسافات مختلفة للتشويك الرئيسي في المكون بين الفتحة الأمامية للليزر ومحور الألياف.

الاستنتاجات المستخلصة:

1- يكون اضطراب الليزر الألياف معتمد على عدد الفوتونات على نطاق زمني في حالة تدفق ضوئي قوي كمسافة 4.4 متر ونوكس

المتقدمة في أعضاء قيمته عند عتبة الليزر وسلوك التضكين المحراري 4

مساويا 5 متر.
 المنحنى الطيفي المناطر للضوضاء النسبية يتميز بقيم عالية للذرة عند التردد المنحنى للتنويف الخارجي$f_0$ ومصاعبته بعكس المنحنى المميز للذرة المنعزل.

 الذي يظهر قيمة واحدة عند تردد الاستراحات المميز للتنويف الداخلي للذرة.

 تعني هذه النتائج أن انغشت ضوء للذرة ينتج عند التردد $f_0$, وأن التفاوتة العكسية تسبب في رفع مستوى الضوضاء بقيمة رابعين كثيبيد. كثيبي.