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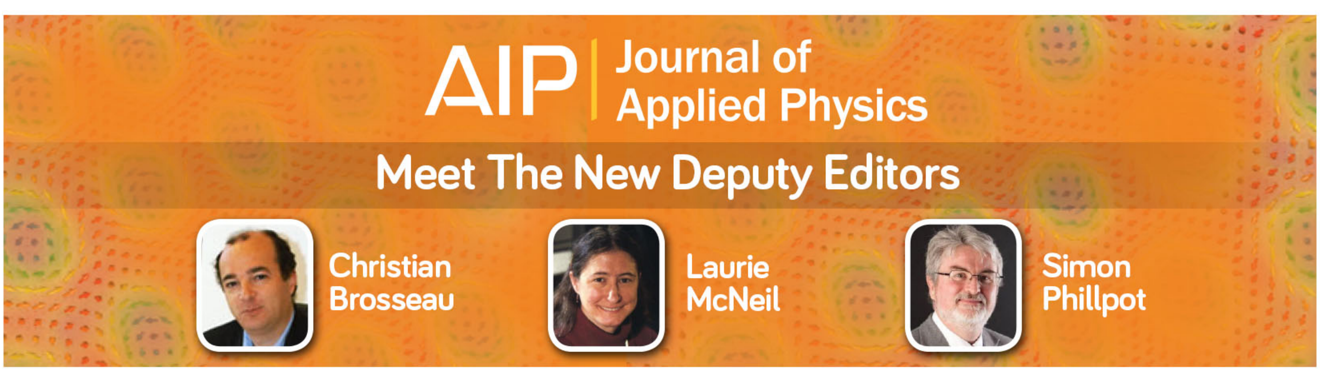

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Deriving of single intensive picosecond optical pulses from a high-power gain-switched laser diode by spectral filtering

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Single 25 ps/16 W optical pulses were achieved by spectral filtering from a multiheterostructure gain-switched laser diode with its quasisteady-state modes suppressed by a factor of 10^3 as compared with the peak power. A significant transient spectrum broadening makes this possible provided that a very high dI/dt rate of the pumping current pulse is used. A simple numerical model is suggested which describes adequately both the spectral and transient features of the observed phenomenon. It follows from the model that single picosecond optical pulses can be obtained from any type of high power semiconductor laser. © *1998 American Institute of Physics.* [S0021-8979(98)01320-6]

I. INTRODUCTION

A number of semiconductor laser applications, such as optical radars, laser tomography, time imaging, and laser-induced fluorescence studies, require powerful single optical pulses a score or two of picoseconds in width. An additional requirement of the absence of an emission tail after the pulse may be important for some of these applications.

An interesting option for achieving this goal by making use of an artificially induced saturable absorber has been discussed lately.[1,2] The absorber is formed in this case by the implantation of heavy ions of high energy through the laser mirror, thus creating a region with an extremely short carrier lifetime. This absorbing area operates as an optical shutter which augments the energy that accumulates in the laser cavity and suppresses long-duration light emission followed by a short spike. The method seems to be universal for any semiconductor laser, but the special implantation regime has to be adjusted for each type of laser diode.

Alternatively, simple gain-switching mode without any special laser treatment allows highly intensive (over 100 W) picosecond range optical pulses to be achieved with a 45 W laser diode[3] when a very high dI/dt rate (30 A/300 ps) is used for the pumping. The relatively low repetition rate of the optical pulses in this case (a few kHz) is a consequence of limitations imposed by the driving circuit. An intensive picosecond pulse can in principle be obtained from any type of laser diode provided that two conditions are satisfied, namely that the current pulse amplitude should exceed the threshold current by a factor of at least 10 and the rise time of the current pulse should be as short as the lasing time delay.[4] Note, however, that relaxation oscillations and quasisteady-state modes manifest themselves after the first intensive optical spike, so that the laser response contains an emission tail. This may cause problems in some applications. In order to suppress these harmful modes, the current pulse must be so short (a few hundreds of picoseconds)[4] that it is hardly realistic in high-power lasers when a high current pulse amplitude (over 10 A) has to be used.

The actual derivation of single picosecond-range optical pulses by means of gain-switching effect in semiconductor lasers is well known from the early 1980's. A pulse duration of less than 7 ps for a 100-μm-long cavity has been obtained in a bulk structure,[5] while 1.8 ps pulses have been demonstrated in a multiple quantum well (MQW) structure[6] in a gain-switching operation regime. A pumping pulse duration of less than 200 ps is typically needed to suppress second relaxation-oscillation peaks in order to implement this approach. The problem of producing extremely short pumping current pulses of high amplitude, as high as several dozen amperes, does not allow this method to be employed for deriving high power single optical pulses.

We show in this work that the well-known transient spectrum broadening effect (see Ref. 7) can be so significant under high current pumping conditions that simple spectral filtering allows the first optical side-mode relaxation oscillation to be efficiently separated from the steady-state lasing modes. The ratio of the amplitude of the first oscillation to that of the second one is significantly increased as well, owing to the spectral dependence of the transient peak gain. Consequently the amplitude of the single optical pulse can exceed the intensity of the emission tail by a few orders of magnitude, and its power is comparable with the nominal power for a laser diode. The numerical model suggested here describes well all the observed spectral and transient features of the phenomenon.

II. METHOD

Commercial multiheterostructure laser diodes (type CVD-193, Laser Diode, Inc.) with an AlGaAs active region were used to illustrate of the spectral filtering method for the gain-switching mode. This is a broad-stripe laser which contains three stacked diodes with a 250 μm$\times$200 μm emitting area. The threshold current is about 1.3 A, the wavelength of

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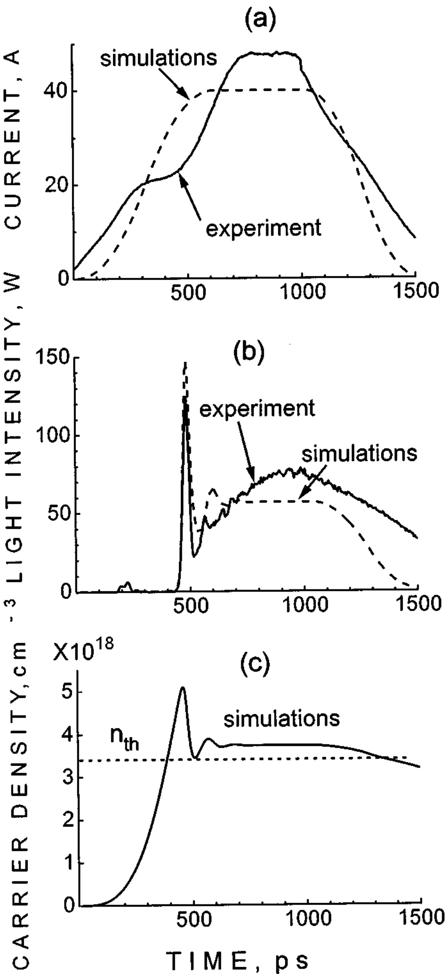

FIG. 1. Experimental and simulated optical pulse waveforms (b) and corresponding transient carrier concentration in the active region of the laser diode (c). The dotted line denotes the threshold concentration. The pumping current pulses used in the experiment and in the simulations are also shown (a).

the steady-state lasing at room temperature is around 850 nm, and the peak power of the laser is about 45 W with a current amplitude of 20 A. A special current pulse generator[3] was used which allowed a 20–30 A current to be achieved with a risetime of 300 ps and a pulse duration of 1 to 2 ns. The repetition frequency of 3 kHz used in our experiments was a consequence of limitations imposed by the pumping circuit. The laser diode should in principle tolerate the same pumping conditions with $\sim 10^2$ higher repetition rate.

The experimental current and optical pulse waveforms, together with the simulated optical pulse waveform and the transient carrier concentration in the active region of the laser diode are presented in Fig. 1. The current used in the simulations is also shown (the numerical model used for the simulations will be presented later).

One can see that the threshold concentration is exceeded by $\sim 2\times 10^{18}$ cm^{-3} during the transient process. This value is significantly higher than the transparency concentration in GaAs and, accordingly an essential transient spectrum broadening towards a higher photon energies can be expected, since the essential fraction of the excess carriers should occupy the high-energy states immediately before the lasing occurs. Transient spectrum broadening towards the lower energies is expected as well, due to band renormalization when the carrier density is very high. On account of dumping, the significant spectrum broadening takes place only during the first relaxation oscillation, and thus a time-isolated light spike can be achieved if the quasisteady-state modes are suppressed by the spectral filtering.

Monochromatic traces from the gain-switching pulse were measured with a streak camera having a time resolution of 2 ps and a monochromator with a spectral resolution of 0.1 nm in order to verify the transient spectrum broadening. The spectrum-integrated optical pulses were recorded by means of a 23 GHz oscilloscope and a 26 GHz p-i-n photodetector. The time-integrated spectra with a resolution of 0.1 nm and the optical pulse waveforms were measured under identical conditions.

A commercially available bandpass filter (type HQ845/10, Chroma Technology Corp.) with high transparency and steep spectral characteristics [see curve 3 in Fig. 3(a)] was used for the transient mode filtering.

III. EXPERIMENTAL RESULTS

Monochromatic traces measured at a laser temperature of 292 °K and with the same pumping conditions as shown in Fig. 1 are presented in Figs. 2(a), 2(c) and, 2(e). It can be seen that only a short, clean spike of the light intensity manifests itself in the high photon energy range (wavelength 830–837 nm). The same feature can also be observed in the low photon energy band, but here the wavelength range is narrower (852–855 nm) and the spike intensity is lower. Quasisteady-state modes (845–852 nm) should obviously be completely removed by spectral filtering, and modes with a relatively strong second relaxation oscillation (840–845 nm) should be suppressed as well in order to obtain the single short optical spike. A filter should thus be transparent in the 830–837 nm range (for a temperature of 292 °K) and the long-wavelength side of the spectral characteristic should be as steep as possible. It may be assumed from the comparison of the monochromatic traces in Figs. 2(a) and 2(c) that a slope of the filter characteristic of $\sim$0.5 decade/nm with a maximum suppression of $\sim 10^{-3}$ should be sufficient for producing of clean single pulse without dramatic intensity losses, and this will later be confirmed experimentally.

The shift in the laser emission band caused by the change in laser diode temperature was used for fine fitting of the transient spectrum to the spectral characteristics of the filter [see Fig. 3(a)]. Curves 1 and 2 present the time-integrated spectra at temperatures of the laser diode of 302 °K and at 321 °K, respectively. The shift in the emission band is caused by the temperature dependence of the semiconductor band gap. Curve 3 in Fig. 3(a) shows the spectral characteristics of the bandpass filter. The filtered spectrum measured at a temperature of 321 °K is depicted by curve 4 in Fig. 3(a). Curves 1 and 2 in Figs. 3(b) and 3(c) present nonfiltered (b) and filtered (c) optical pulse waveforms at diode temperatures of 302 and 321 °K, respectively. When the temperature is lower, the filter does not suppress the quasisteady-state modes completely, and long-duration light

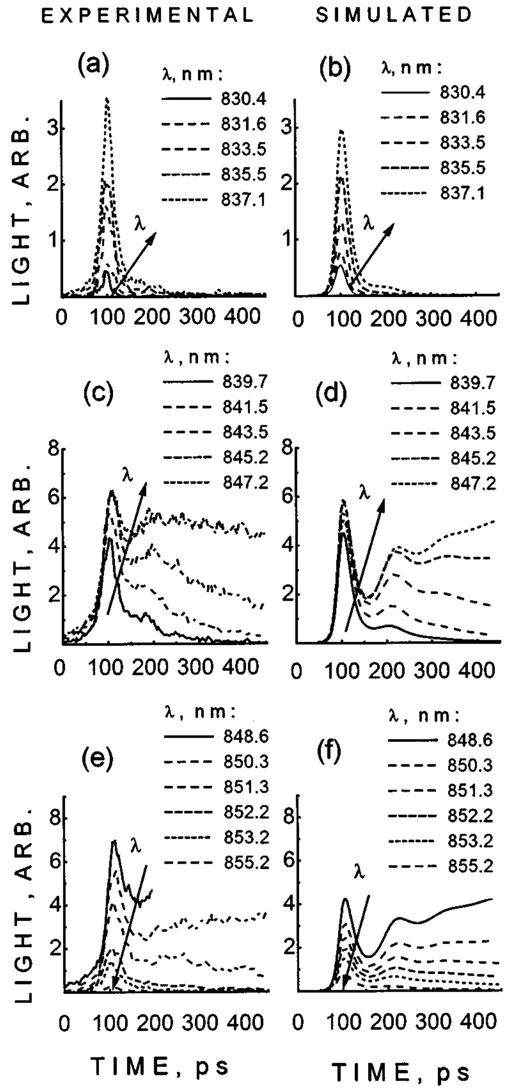

FIG. 2. Experimental and simulated monochromatic traces from the response of the gain-switched laser diode. Diode temperature $T=292$ °K. Modes 17, 18 (wavelengths 857.2 and 859.2 nm, respectively) are omitted because their intensities are negligible.

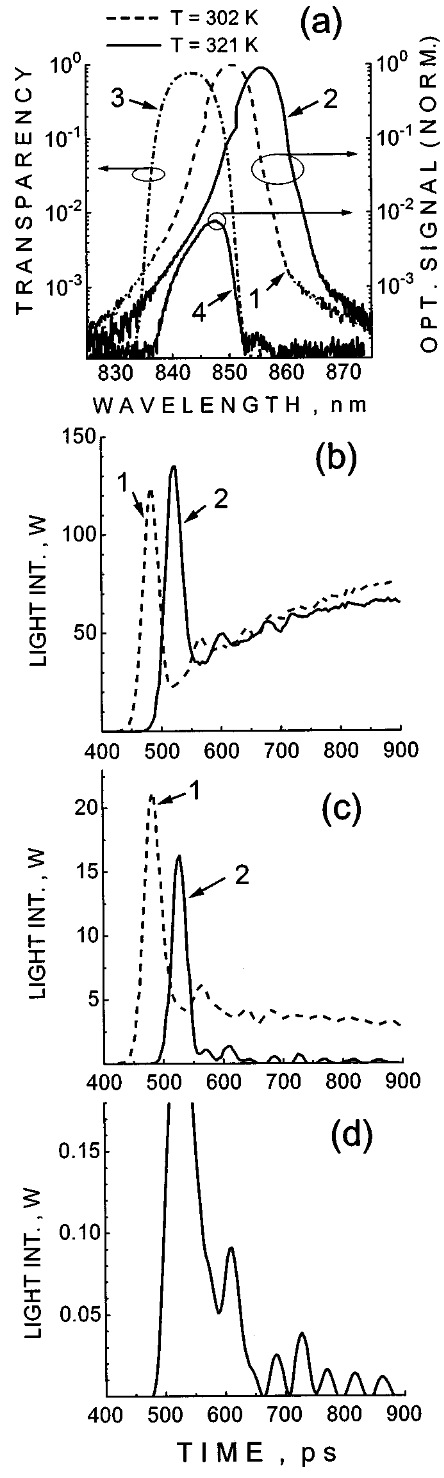

FIG. 3. Time-integrated lasing spectra (a), nonfiltered (b) and filtered (c) optical pulse waveforms. The curves 1 were measured at a laser diode temperature of 302 °K, and the curves 2 at 321 °K. Curve 3 in (a) shows the spectral characteristics of the filter, and curve 4 presents the filtered spectrum at 321 °K corresponding to the single pulse. The bottom of the single pulse [curve 2 in (b)] is shown at a higher amplification in (d).

emission can be observed [see curves 1 in Figs. 3(a) and 3(c)]. The transient spectrum is better fitted to the filter characteristic at the higher temperature, and a single optical pulse with a full width at half maximum (FWHM) of 25 ps and power of 16 W is achieved [curve 2, Fig. 3(c), see also curves 2 and 4 in Fig. 3(a)]. The bottom of the single time-isolated pulse is shown at a higher amplification in Fig. 3(d). The small amplitude ~20 GHz ringing to be seen after this pulse is associated with current oscillations in the receiving channel and does not correspond to the real optical signal (as checked by observing the filtered pulse with a streak camera). No optical signal with an intensity higher than 20 mW thus manifests itself after about 200 ps.

IV. NUMERICAL MODEL AND DISCUSSION

A numerical model based on time-domain multimode rate equations for the carrier and photon densities was developed to describe the above phenomenon quantitatively and to allow further optimization of the experimental conditions.

A quasiuniform carrier distribution in the active area of the laser is assumed, and thus spatially averaged rate equations are used.[8,9] For simplicity, the analysis implies quasi-continuous spectrum of the resonator modes, since wide-strip lasers always present multimode behavior. In view of these conditions the equations describing the multimode transient spectra of a gain-switched laser can be written as follows:

$$\frac{\partial n}{\partial t}=\frac{j(t)}{qd}-R_{\rm sp}n(t)-v_g\sum_m G_m(n,t)S_m(t), \qquad (1)$$

$$\frac{\partial S_m}{\partial t}=v_g\left[G_tG_m(n,t)-\left(\alpha+\frac{1}{L}\log\left(\frac{1}{R}\right)\right)\right]S_m(t), \qquad (2)$$

where n is the time dependent carrier concentration in the active layer of the laser, q is the electron charge, d is the active layer thickness, and $j(t)$ is the pumping current density. $R_{\rm sp}$ is the spontaneous recombination rate, which we define as:

$$R_{\rm sp}=A+Bn+Cn^2. \qquad (3)$$

Here the coefficient A holds for nonradiative recombination, B represents the electron-hole recombination rate, and C corresponds to the rate of Auger recombination. The photon rate equation is written for every lasing mode under consideration. For a total of M modes we solved the set of M equations in the form of (2). Actually, the lasing modes were arbitrarily quantized in such a way that M was selected to be equal to 18 (16 modes correspond to the same wavelength values as listed in Fig. 2, and the two additional modes are mentioned in the figure caption). In these equations S_m is the photon density in the mode m, G_m is the material gain corresponding to the mode m, and G_t is the transverse confinement factor, which is assumed to be equal for all the modes. The parameter α represents the optical material losses and v_g is the velocity of light in the semiconductor medium. L is the cavity length and R is the reflectivity of the device mirrors (assuming that both front and back mirrors are identical).

One important factor for gain-switched laser modelling is the description of the transient gain spectrum. The material gain G_m entering the Eqs. (1) and (2) was considered to be dependent on the carrier concentration, photon energy, and photon density in the corresponding mode. More specifically, the material gain is represented as

$$G_m=G_0(n)\left[1-\left(\frac{E_m^{\rm ph}-E_{\rm max}(n)}{E_0(n)}\right)^2\right][1+\epsilon_m(S_m)]^{-1}, \qquad (4)$$

where $G_0(n)=G_0\cdot(n-n_{\rm tr})$ is the concentration-dependent gain amplitude, approximated by a linear function, $n_{\rm tr}$ is the transparency concentration, and $E_m^{\rm ph}$ is the photon energy. The nonlinear gain coefficient $\epsilon_m(S_m)$ accounts for spectral hole burning and other nonlinear effects which are important at a high photon density. Both the position of the spectral gain maximum and the width of the gain spectrum are assumed to be concentration dependent. The dependences $E_{\rm max}(n)$ and $E_0(n)$, which were approximated by linear functions, were selected to satisfy the following criteria. First, the simulated wavelength of the steady-state lasing mode had to be fitted to the experimental wavelength of the laser LD-193, and second, the approximations for the wavelength and concentration-dependent gain had to provide good agreements with the data for GaAs lasers.[9,10] The resulting approximation for the gain used in the simulations is shown in Fig. 4 (left axis).

The current waveform $j(t)$ in the modelling was chosen to be close to that used in the experiment [see Fig. 1(a)], and the main laser diode parameters were chosen to be close to those of the CVD-193 diode: cavity length $L=550\ \mu$m; cavity width $W=250\ \mu$m; effective active layer thickness $d=0.05\ \mu$m; transparency concentration $n_{\rm tr}=0.7\times10^{18}$ cm^{-3}; gain amplitude $G_0=2500$ cm^{-1}; transverse confinement factor $G_t=0.02$.

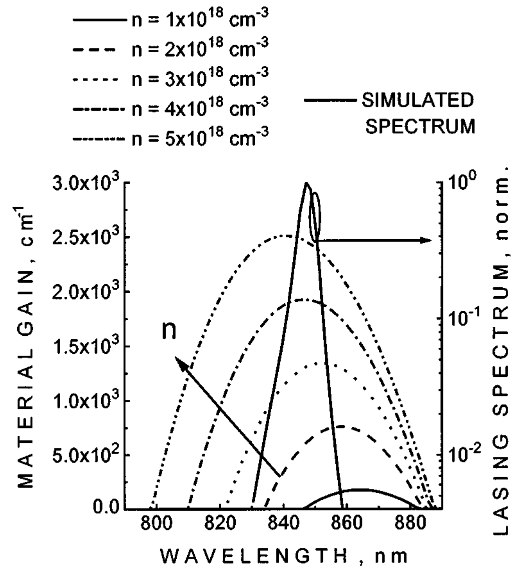

FIG. 4. Material gain spectra used in the simulations (left), and simulated time-integrated lasing spectrum of a gain-switched CVD-193 laser. Lattice temperature $T=292$ °K.

The simulated time-integrated spectrum for the gain-switched laser is shown in Fig. 4 (right axis) in order to illustrate how the dependence of the gain on wavelength defines the transient spectrum.

The monochromatic traces simulated for the same spectral modes as were measured in the experiment are fairly close to the experimentally observed ones [compare (a), (c), (e) and (b), (d), (f) in Fig. 2), the small discrepancy being attributable to the difference between the current pulse waveforms used in the experiment and in the simulations [see Fig. 1(a)].

The simulated laser response modelling the spectral filtering experiment is represented by curves 1 and 2 in Fig. 5, while curve 3 shows the experimental waveform. The abso-

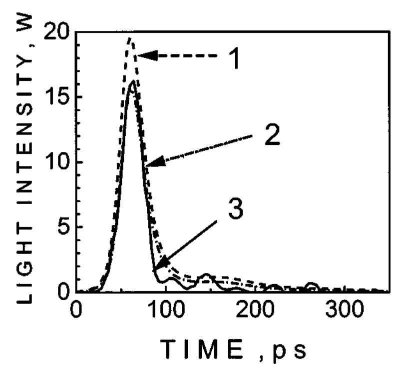

FIG. 5. Simulated (1, 2) and measured (3) single optical pulses obtained by spectral filtering. Curve 1 corresponds to a 9 nm spectral shift of the filter characteristic, and curve 2 to 9.5 nm.

lute optical powers of the spectrally filtered pulses obtained from both the numerical simulations and the experiment are shown. In modelling the monochromatic traces are scaled to the filter transparency and summarized. Note that a temperature of 321 °K was used for fitting the transient spectrum to the filter characteristic in the experiment, while the simulations were performed for the temperature of the monochromatic trace measurements (292 °K), so that a spectral shift of the filter characteristic by ≈9 nm towards short wavelengths should be used when modelling the filtering experiment (curve 1, Fig. 5). A better fit of the simulated response to the experiment was achieved for a spectral shift of 9.5 nm (curve 2, Fig. 5). An additional 0.5 nm spectral shift corresponds to a change of ∼1.5 °K in the laser diode temperature. Thus the difference in amplitude between the simulated and experimental filtered pulses does not exceed the error in diode temperature control and measurement, which was about 2 °K in our experiments.

A detailed comparison of the experimental and simulated results shows that the main mechanism responsible for the abnormally wide lasing spectrum is carrier concentration transient overshoot and the corresponding gain spreading. This overshoot can be significant only if the pumping current rise time is small enough for a certain peak current value. According to our simulations, however, the amplitude of the concentration overshoot tends to saturate at rise times of less than about 0.25–0.3 ns. This saturation is caused by the characteristic electron-photon relaxation time. Thus for a given laser structure there exists a sufficient dI/dt value for the pumping pulse which allows the mostly efficient optical power to be obtained in a single pulse. No significant advantage can be expected from any further increase in the dI/dt rate. The power of the single optical pulse can be further increased by optimizing the laser diode parameters.

V. CONCLUSIONS

A significant transient spectrum broadening in the response of a gain-switched laser diode was demonstrated both experimentally and by simulations in the presence of a short rise time and a high-amplitude current pulse. It was shown that only a picosecond-range optical spike manifests itself in the transient modes, related to both high and low photon energy bands. This enabled a single 25 ps/16 W optical pulse to be achieved by spectral filtering from the output of the gain-switched semiconductor laser with a peak power of 45 W.

A numerical model was suggested for the phenomenon, and good agreement was achieved between the experimental and simulated optical traces and the transient spectra.

The method suggested here seems to be universal for practically any type of semiconductor laser thus providing a way of obtaining single short pulses with the various power levels and wavelengths achievable nowadays in the laser diodes.

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