Transient response of an optically pumped short-cavity semiconductor laser

Guido Pompe, Thomas Rappen, and Martin Wegener
Institut für Physik, Universität Dortmund, D-44221 Dortmund, Germany
(Received 2 August 1994)

We study the dynamics of a single-mode short-cavity laser consisting of a 1-μm-thick layer of bulk semiconductor sandwiched between dielectric mirrors and excited by optical femtosecond pulses. The emission is time resolved by an up-conversion technique with time resolution of 250 fs. The experimental evidence for low and high excitation is compared with model calculations and is discussed in the framework of recent microscopic theories. From this comparison we conclude that the heating of the carrier distributions due to stimulated emission has a dramatic influence on the temporal dynamics of the emission.

I. INTRODUCTION

The coupled electron-phonon and electron-photon dynamics in semiconductor lasers are of great interest; however, neither is well understood. The small cavity length of short-cavity semiconductor lasers (SCSL's) offers the unique opportunity to study laser dynamics in a system in which the medium can couple exclusively to one longitudinal mode of the light field. This can be realized by, for example, a slice of semiconductor in a cavity, comparable in thickness to the wavelength of light. Such a well-defined and physically transparent situation is attractive in order to obtain a detailed microscopic understanding. This has encouraged recent theoretical approaches.[1–3] Moreover, potential applications of semiconductor microcavity lasers have recently attracted considerable attention.[4,5]

Previous experimental studies on more complex, device-oriented semiconductor microlasers had limited temporal resolution[6,7] and contained no simultaneous spectral information. In the experiments presented here we focus on the dynamics of an optically pumped SCSL, employing simultaneous spectral and 250-fs time resolution. The data reveal valuable insights into the coupled electron-photon dynamics in semiconductor lasers.

II. EXPERIMENT

A set of samples particularly well suited for optical excitation has been prepared. A 1-μm-thick layer of bulk $In_xGa_{1-x}As$, lattice matched to the InP substrate, is grown by low-pressure metal-organic vapor-phase epitaxy. A corresponding absorption spectrum is depicted in Fig. 1(a). We remove the InP in an area of ≈ 1 mm^2 by selective etching with concentrated HCl, in order to evaporate dielectric mirrors on both sides.[8] Each mirror consists of eight pairs of $\lambda/4$ layers ($\lambda = 1.55$ μm) of SiO_2 ($n = 1.46$) and Ta_2O_5 ($n = 2.10$), yielding a reflectivity of $R = 0.99$ at 1.55-μm wavelength. A corresponding measured transmission spectrum can be seen in Fig. 1(b). Somewhat similar samples have been described previously.[9] The samples discussed here exhibit only one lasing mode around 1.49-μm wavelength [see Fig. 1(c)]. This mode is situated 100 meV above the fundamental gap [$E_g = 0.73$ eV; see Fig. 1(a)]. The adjacent longitudinal modes are outside the high reflectivity band of the mirrors, as expected from the design of the samples and verified experimentally (the mode spacing is 116 meV, corresponding to an effective cavity length of 1.55 μm).

For the optical excitation we use transform-limited Gaussian pulses with a duration of 250 fs at a 1-kHz repetition rate from an amplified passively mode-locked color-center laser, frequency doubled to a photon energy of 1.56 eV in a 1-mm-thick crystal of β-barium borate (BBO). In this spectral range the dielectric mirrors of the SCSL's are transparent. Pulse energies up to 1 μJ are available. The laser beam is focused on a spot diameter of about 30 μm. Because we were concerned about possible transverse multimode behavior of the SCSL emission at this rather large spot size, we have repeated the experiments using much smaller (5-μm diameter) spots deliver-

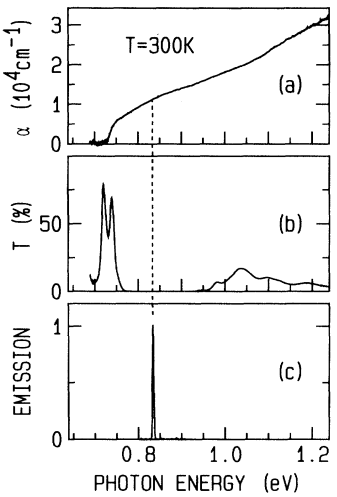

FIG. 1. Experiment: (a) absorption spectrum of the 1-μm layer of $In_xGa_{1-x}As$ on the InP substrate; (b) transmission spectrum of the isolated layer sandwiched between dielectric mirrors; and (c) emission spectrum slightly above the lasing threshold.

ing similar results. Moreover, the SCSL emission is inspected with an infrared camera system and exhibits a Gaussian profile for both excitation spot sizes and all excitation levels, indicating transverse single-mode operation, i.e., the behavior of the emission does *not* depend on the transverse coordinate. To further check this important point we also performed the measurements described below with an aperture (in an intermediate image plane), revealing no dependence of the behavior as a function of the transverse coordinate.

The time-integrated SCSL emission is spectrally resolved by a 0.25-m spectrometer connected to a liquid-nitrogen-cooled germanium multichannel analyzer (1-meV resolution). A typical time-integrated emission spectrum is shown in Fig. 1(c). The energy incident onto the sample, held at room temperature, is 2 nJ. If the pump energy is reduced to 1.5 nJ, the emission drops by more than three orders of magnitude, indicative of a well-defined laser threshold. An increase of the incident energy leads to the scenario depicted in Fig. 2. A considerable asymmetric broadening, finally reaching a full width at half maximum (FWHM) of more than 20 meV at 30-nJ incident pump energy is observed. The incident pump energies can only be correlated roughly with actual carrier densities. Using a spot diameter of 30 μm and assuming that all photons are absorbed within the 1-μm-thick layer of $In_xGa_{1-x}As$, we estimate a carrier density of 10^{19} cm^{-3} at an excitation level of 2 nJ. The actual densities, however, are somewhat lower because of Pauli blocking at the pump photon energy. Pauli blocking becomes even more pronounced at higher excitation levels, hence the relation between incident energy and carrier density is no longer linear.

In order to study the temporal dynamics we up-convert the SCSL emission with a fraction of the pump light in a 0.5-mm-thick crystal of $LiIO_3$. The sum frequency (around 2.39 eV photon energy) is fed into another 0.25-m spectrometer connected to a liquid-nitrogen-cooled charge-coupled device (CCD) camera (resulting in 2-meV resolution). Spectra are recorded as a function of time delay between emission and reference pulse in steps of 0.5 ps. A typical acquisition time for a set of 100 spectra is 3 min. Clearly, the overall spectral resolution is given by the time-energy uncertainty, hence for 250-fs time resolution by about 7-meV FWHM. The incident pump light can be attenuated by means of calibrated neutral density filters. The time delay introduced by these filters has been measured independently, and the data are corrected correspondingly (with an error smaller than 0.25 ps). The zero time is determined by up-converting a fraction of the fundamental of the femtosecond laser. The corresponding experimental error due to the different refractive indices (around 1.56- and 0.78-eV photon energy) of the glass in the setup is estimated to be less than 1 ps.

Data for excitation slightly above [Fig. 3(a), where the pump energy is 2.5 nJ] and well above the threshold [Fig. 3(b), where the pump energy is 15 nJ] are depicted in Fig. 3. For weak excitation the SCSL emission exhibits a rather large time delay with respect to the pump pulse, arriving at $t=0$. Both rise and decay extend over several ps, exhibiting a small redshift of the laser line with time. This scenario gradually changes toward higher excitation. At very high excitation levels [Fig. 3(b)] the SCSL emission exhibits a sharp (400-fs time constant) rise after a time delay of several ps, a fast overshoot ($\sim$1 ps), another slower rise, and a long trailing edge. The emission exhibits a huge chirp (20 meV) from large to small photon energies. Hence the spectral width seen in the time-integrated data (see Fig. 2) is entirely caused by a chirp of the single optical mode.

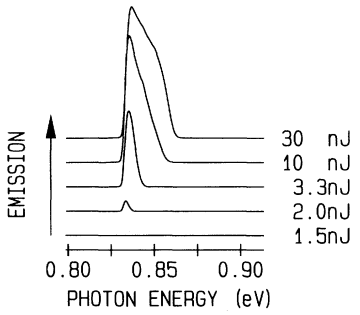

FIG. 2. Experiment: Time-integrated emission spectra of the short-cavity semiconductor laser for increasing pump energy (as indicated). For clarity, the spectra are displaced vertically.

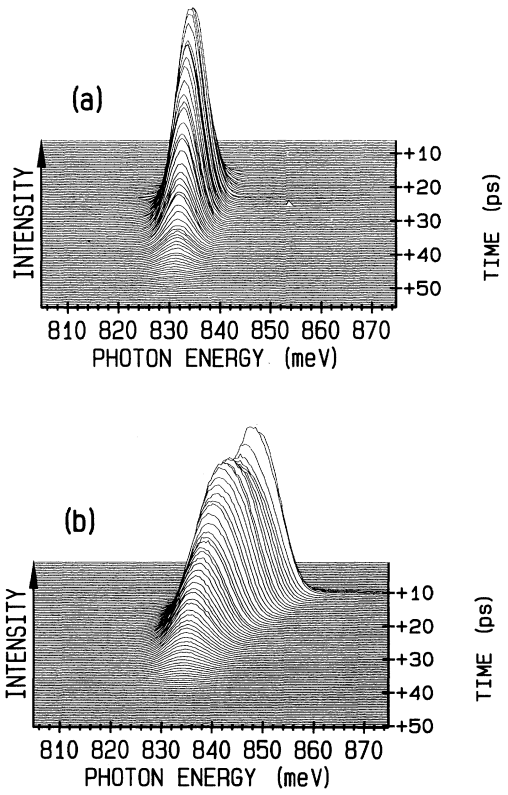

FIG. 3. Experiment: Time-resolved emission spectra of the short-cavity semiconductor laser for (a) low and (b) high excitation (see text). In each case, 100 spectra in steps of 0.5 ps are displaced vertically.

III. DISCUSSION AND SIMPLE MODEL

After the initial optical excitation, the excited carriers lose their large excess energy by carrier-carrier and carrier-phonon scattering. Carrier-carrier scattering is known to lead to a considerable occupation of low-energy states on a time scale well below 100 fs (Ref. 10) (also exciting with a large excess energy). The cooling of the resulting hot carrier distribution takes place on a time scale on the order of 1 ps (Refs. 11 and 12) (measured under comparable high-density conditions of a semiconductor optical amplifier within the same material system). The loss of photons out of the cavity is governed by the photon lifetime, which is directly related to the reflectivity R of the mirrors by $\tau_p=-Ln/[c_0\ln(R)]$, with L being the cavity length, c_0 the vacuum velocity of light, and $n=3.3$ the refractive index. For the present mirrors with $R=0.99$ and the effective cavity length $L=1.55$ μm we obtain $\tau_p=1.7$ ps.

Clearly, the observed dynamics (Fig. 3) is not directly related to any of these time constants. In order to model the experimental evidence we employ a largely simplified version of the theory described in Ref. 3. We use a two-band model within the effective-mass approximation. Interband Coulomb correlations and band-gap renormalization are neglected. The excitation process is modeled by $\Gamma_{\text{pump}}=\delta(t)\times N(t=0)$. The following extended coupled rate equations describe the dynamics of the total carrier density N, the photon density p of the laser mode, and the common temperature T of electrons and holes:

$$\frac{dN}{dt}=-\Gamma_{\text{spont}}-\Gamma_{\text{stim}}+\Gamma_{\text{pump}}\ ,$$

$$\frac{dp}{dt}=+\eta\Gamma_{\text{spont}}+\Gamma_{\text{stim}}-\Gamma_{\text{loss}}\ ,$$

$$\frac{dT}{dt}=+\Gamma_{\text{heat}}-\Gamma_{\text{cool}}\ ,$$

with the rate for stimulated emission (SE) $\Gamma_{\text{stim}}=c_0/n(\hbar\omega)\times g(\hbar\omega,N,T)\times p$, where $\hbar\omega$ is the photon energy of the laser mode.[13] The gain coefficient g is given by

$$g(\hbar\omega,N,T)=-g_0\hbar\omega\Theta(\hbar\omega-E_g)\sqrt{\hbar\omega-E_g}\times(1-f_e-f_h)\ .$$

The Fermi-distribution functions $f_e(k,N,T)$ and $f_h(k,N,T)$ [depending on $\hbar\omega$ via the energetic dispersions $E_{e,h}(k)$] of electrons and holes, respectively, are computed via the chemical potentials using the Padé approximation[14] and the well-known effective masses of electrons m_e and holes m_h of $\text{In}_x\text{Ga}_{1-x}\text{As}$. The coupling coefficient of the spontaneous emission into the laser mode η comprises both a spectral weighting factor and a geometrical coupling factor.[3] The rates for spontaneous emission $\Gamma_{\text{spont}}=N/\tau_N$ and losses of the cavity $\Gamma_{\text{loss}}=p/\tau_p$ are assumed to be exponentials.

SE ejects carriers with a below average kinetic energy from the system. After fast thermalization the carriers acquire a higher temperature because carrier-carrier scattering conserves the total energy of the carrier system. This heating due to SE in SCSL's has been pointed out and discussed in detail in Ref. 15 (within the framework of a microscopic theory). Here we follow a much simpler approach. We assume a constant total energy of the combined system[16] of electrons (treated in the degenerate limit) and holes (using the Boltzmann approximation) after the emission process. For infinitely fast carrier-carrier scattering we derive

$$\Gamma_{\text{heat}}=+\Gamma_{\text{stim}}\left[\frac{T}{N}+\frac{1}{3}\left[\frac{3}{8\pi}\right]^{2/3}\frac{h^2}{k_Bm_e}N^{-1/3}-\frac{2}{3}\frac{(\hbar\omega-E_g)}{k_BN}\right]\ .$$

The emission of phonons, modeled by $\Gamma_{\text{cool}}=(T-T_0)/\tau_T$ reduces the average kinetic energy of the carriers, hence describing the cooling of the carrier temperature T to the lattice temperature T_0 with a time constant τ_T.

The photon energy of the laser mode $\hbar\omega$ is given by the condition for constructive interference in the cavity: $\omega/c_0\times n(\hbar\omega)L=m\pi$, where m is an integer. The change of the refractive index $\Delta n(\hbar\omega,N,T)$, which is computed via a Kramers-Kronig transformation of the gain spectrum, gives rise to an energetic shift of the laser mode. For small shifts we can perform an expansion and obtain

$$\frac{\hbar\omega-\hbar\omega_0}{\hbar\omega_0}\approx-\frac{\Delta n(\hbar\omega_0)}{n(\hbar\omega_0)}\ .$$

Finally, the δ-shaped SCSL emission (with amplitude p) is convoluted with the spectrum of a 250-fs Gaussian pulse, allowing for a direct comparison with the experimental data obtained by up-conversion.

For the modeling we use the parameters $\tau_p=1.7$ ps, $T_0=300$ K, $T(t=0)=1000$ K, $n(\hbar\omega_0=0.828\text{ eV})=3.3$, $m_e=0.041\times m_0$, $m_h=0.377\times m_0$ (m_0 is the free-electron mass), and $E_g=0.73$ eV. $g_0=3.81\times10^4\ \text{cm}^{-1}\ (\text{eV})^{-3/2}$ is chosen such that the absorption coefficient at 0.83-eV photon energy [$=-g(\hbar\omega_0,N=0)=10^4\ \text{cm}^{-1}$] corresponds directly to the experiment [see Fig. 1(a)]. The only adjustable parameter is $\tau_T=2$ ps, which is chosen to match the experiment. Note that this choice is slightly longer than the literature values (~1 ps) discussed above.[11,12] This can possibly be attributed to the effect of hot phonons,[17] which additionally delays the cooling of the carriers. The parameters $\tau_N=1$ ns and $\eta=10^{-4}$ are not well known; however, they influence the results only marginally even when varied by an order of magnitude. The threshold density in the model is $N(t=0)=1.8\times10^{18}\ \text{cm}^{-3}$.

In Fig. 4 the computed time-resolved emissions for low (a) [$N(t=0)=2.2\times10^{18}\ \text{cm}^{-3}$] and high (b) [$N(t=0)=6.0\times10^{18}\ \text{cm}^{-3}$] initial carrier densities are depicted. As in the experiment [compare Figs. 3(a) and 3(b) with Figs. 4(a) and 4(b)] the emission is strongly chirped for high excitation levels. Even close to threshold the chirp is considerable. The chirp is due to the carrier distribution functions changing in time leading to a redshift of the laser emission via the increasing refractive

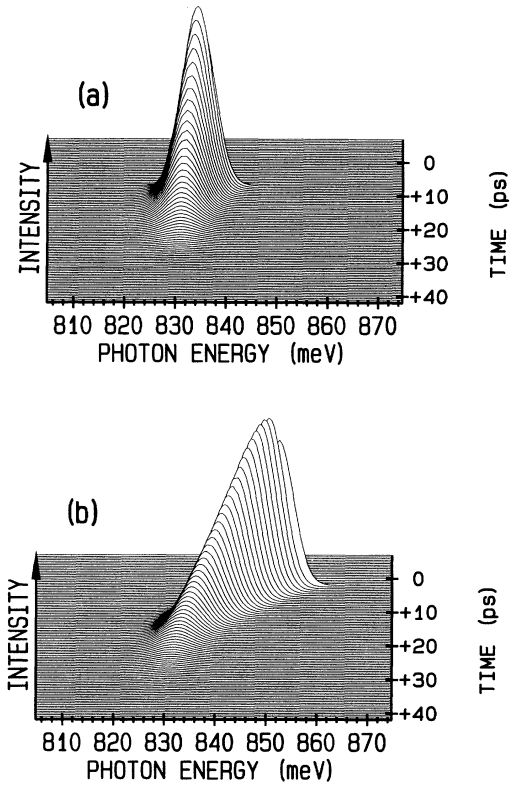

FIG. 4. Model: Time-resolved emission for initial carrier densities of (a) 2.2×10^{18} cm^{-3} and (b) 6.0×10^{18} cm^{-3}. These spectra have to be compared with Fig. 3.

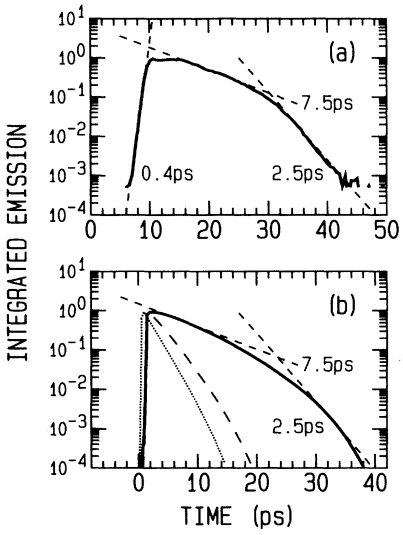

FIG. 5. Comparison: Spectrally integrated emission vs time plotted on a logarithmic scale. (a) Experiment, corresponding to Fig. 3(b). (b) Model, corresponding to Fig. 4(b). For the dashed curve in (b) the heating due to stimulated emission has been neglected; for the dotted curve the temperature is fixed at 300 K (see text). For clarity the three curves are normalized to equal peak heights. The various dashed straight lines in (a) and (b) with respective time constants are guidelines to the eye.

index. The temporal response is governed by the negative feedback brought about by the heating due to SE. For large SE the carrier system is heated, reducing the gain at the laser mode, which in turn reduces the rate of SE and hence slows down the temporal response. Consequently, the heating due to SE leads to a highly nonexponential decay of the SCSL emission, in particular for high excitation levels, hence large rates of SE.

Figure 5 compares the spectrally integrated emission [corresponding to Figs. 3(b) and 4(b), respectively] on a logarithmic scale exposing the nonexponential behavior. The experiment and simple model are in good qualitative agreement. Neglecting the carrier heating, i.e., $\Gamma_{\text{heat}}=0$ in our model [the dashed curve in Fig. 5(b)] leads to a striking disagreement with the experimental evidence. In particular, the emitted pulse decays far too fast. The assumption of a constant temperature ($T=300$ K) [dotted curve in Fig. 5(b)] even enhances the discrepancy. This clearly demonstrates the importance of the heating due to SE for the transient response of the SCSL. The temperature rises by about 200 K at the onset of lasing in Fig. 4(b). This considerable amount of heating of the carriers is consistent with recent predictions based on a microscopic theory.[15] The heating due to SE has quite recently also been discussed in the context of the cw linewidth of a semiconductor microdisk laser.[18]

The overall agreement between the experimental evidence and simple model is rather good; however, let us finally mention some discrepancies. The time delay between the pump pulse and the onset of lasing, the initial overshoot, and the change of the linewidth in time at high excitation levels, respectively, are not well reproduced. These features can most likely be described by the level of description of Refs. 1–3 which, however, requires a substantially larger numerical effort and is well beyond the scope of this paper.

IV. CONCLUSIONS

In conclusion we have studied the dynamics of a single-mode short-cavity semiconductor laser excited by optical femtosecond pulses. In contrast to excitation slightly above threshold, the transient laser emission exhibits a sharp switch-on (400-fs time constant) and is strongly chirped for high excitation levels. A comparison of the experimental data with simple model calculations reveals the importance of the carrier dynamics, in particular the heating of the carrier distributions due to stimulated emission for the transient response of the laser emission. It would be very interesting to compare directly the experimental evidence with more advanced recent microscopic theories. This could improve the understanding of the remaining discrepancies.

ACKNOWLEDGMENTS

The research of M.W. was supported by the Alfried Krupp-Föderpreis für junge Hochschullehrer of the

Krupp-Stiftung. T.R. acknowledges support by the DFG-Graduiertenkolleg Festkörperspektroskopie. We thank N. Agrawal for providing the wafer of $In_xGa_{1-x}As$, F. Knop for the preparation of the samples, and M. Wehner for assistance in the experiment. We are grateful to E. O. Göbel for lending us the BBO crystal. Stimulating discussions with F. Jahnke and S. W. Koch are acknowledged.

[1]K. Henneberger, F. Herzel, S. W. Koch, R. Binder, A. E. Paul, and D. Scott, Phys. Rev. A **45**, 1853 (1992).

[2]J. Jahnke, S. W. Koch, and K. Henneberger, Appl. Phys. Lett. **62**, 2313 (1993).

[3]F. Jahnke, K. Henneberger, W. Schäfer, and S. W. Koch, J. Opt. Soc. Am. B **10**, 2394 (1993).

[4]J. L. Jewell, J. P. Harbison, A. Scherer, Y. H. Lee, and L. T. Florez, IEEE J. Quantum Electron. **27**, 1332 (1991).

[5]S. L. McCall, A. F. J. Levi, R. E. Slusher, S. J. Pearton, and R. A. Logan, Appl. Phys. Lett. **60**, 289 (1992).

[6]J. L. Jewell, K.F. Huang, K. Tai, Y. H. Lee, R. J. Fischer, S. L. McCall, and A. Y. Cho, Appl. Phys. Lett. **55**, 424 (1989).

[7]D. Tauber, G. Wang, R. S. Geels, J. E. Bowers, and L. A. Coldren, Appl. Phys. Lett. **62**, 325 (1993).

[8]The commercial dielectric mirrors were applied by Laseroptik GmbH, Garbsen, Germany.

[9]D. G. Deppe, S. Singh, R. D. Dupuis, N. D. Gerrard, G. J. Zydzik, J. P. van der Ziel, C. A. Green, and C. J. Pinzone, Appl. Phys. Lett. **56**, 2172 (1990).

[10]T. Elsässer, J. Shah, L. Rota, and P. Lugli, Phys. Rev. Lett. **66**, 1757 (1991).

[11]K. L. Hall, J. Mark, E. P. Ippen, and G. Eisenstein, Appl. Phys. Lett. **56**, 1740 (1990).

[12]G. Eisenstein, J. M. Wiesenfeld, M. Wegener, G. Sucha, D. S. Chemla, S. Weiss, G. Raybon, and U. Koren, Appl. Phys. Lett. **58**, 158 (1991).

[13]At this point, $\hbar\omega$ can be approximated by the photon energy of the laser mode at low densities $\hbar\omega_0$. We have numerically verified that this only leads to marginal deviations from the exact result.

[14]C. Ell, R. Blank, S. Benner, and H. Haug, J. Opt. Soc. Am. B **6**, 2006 (1989).

[15]F. Jahnke, and S. W. Koch, Opt. Lett. **18**, 1438 (1993).

[16]It is also possible to derive closed expressions for the opposite limit, i.e., separate energies and temperatures for electrons and holes, respectively. For the electrons a Sommerfeld expansion and the Padé approximation have to be employed. In this case a larger heating results for the electrons; however, the influence on the transient SCSL emission is somewhat reduced.

[17]C. Y. Tsai, L. F. Eastman, and Y. H. Lo, Appl. Phys. Lett. **63**, 3408 (1993).

[18]U. Mohideen, R. E. Slusher, F. Jahnke, and S. W. Koch, Phys. Rev. Lett. **73**, 1785 (1994).