Stability of Pulse Emission and Enhancement of Intracavity Second-Harmonic Generation in Self-Mode-Locked Quantum Cascade Lasers

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***Abstract*—We report the observation of stable pulse emission and enhancement of intracavity second-harmonic generation (SHG) in self-mode-locked quantum cascade (QC) lasers. Down-conversion of the detector signal by heterodyning with an RF signal allows the direct observation of the pulsed laser emission in the time domain and reveals a stable train of pulses characteristic of mode-locked lasers. The onset of self-mode locking in QC lasers with built-in optical nonlinearity results in a significant increase of the SHG signal. A pulse duration of ∼12 ps is estimated from the measured increase of the SHG signal in pulsed emission compared to the power expected for the SHG signal in CW emission. This value is in good agreement with the pulse duration deduced from the optical spectral width.**

***Index Terms*—Mode-locked lasers, nonlinear optics, pulsed laser, pulse generation, semiconductor lasers, ultrafast optics.**

I. Introduction

QUANTUM CASCADE (QC) lasers are semiconductor lasers based on intersubband transitions emitting in the mid-infrared (IR) wavelength range [1]–[3]. This spectral region is technologically and scientifically important for chemical and biological sensing [4] since many molecules have characteristic absorption features in the mid-IR. Recent progress in QC lasers includes the demonstration of broadband QC lasers, [6] room-temperature CW operation of the QC lasers, and terahertz QC lasers [7] and expands the potential area of applications and opens new directions of research.

One of the advantageous features of the QC laser is ultrashort pulse generation in the mid-IR. Active and passive mode-locking of QC lasers have recently been observed [8], [9]. The origin of passive mode-locking was interpreted as due to a new kind of Kerr lensing mechanism, in which the refractive index nonlinearity arises from the giant optical Kerr effect of the intersubband transition [10], [11] rather than from the nonlinearity of the host medium. However, many properties of mode-locked QC lasers, such as pulse width and shape, have not been measured. Second-order autocorrelation measurements, which are the ultimate test of pulse formation and provide a reliable measurement of the pulse width, have not been carried out yet due to the limited conversion efficiency of nonlinear crystals in the mid-IR and the relatively limited power of QC lasers. Also, no direct measurements in the time domain have been performed, due to the very high repetition rates (∼10–20 GHz) of mode-locked QC lasers.

In this study, we discuss the properties of self-mode-locking in QC lasers such as the stability of the pulsed emission and the increase of the second-harmonic generation (SHG) peak optical intensity above the transition from CW emission to mode-locking. We first report the stability of the pulsed emission of mode-locked QC lasers over a wide current range. We use an RF downconversion method that enables the direct observation of pulsed laser emission in the time domain. The oscilloscope traces show a stable train of pulses at the cavity round-trip frequency that is characteristic of mode-locked lasers. The pulse train is stable over a time scale of tens of nanoseconds.

Second, we observed a significant increase of the intracavity SHG above the onset of the mode-locking. The observed enhancement of SHG is a direct evidence of the increase in peak optical intensity and confirms a transition of the laser output radiation from CW to pulsed emission. The increase of the SHG power allows us to estimate the pulse duration (∼10 ps) in agreement with that calculated from the optical spectral width.

This paper is organized as follows. Section II describes the downconversion method for the time-domain measurements and the observed stability of mode-locked QC lasers. In Section III, we report the increase of the intracavity SHG in mode-locked QC lasers and estimate the pulse duration.

II. Time-Domain Measurements and Stability of Self-Mode-Locked QC Lasers

Self-mode-locking of QC lasers has been described extensively in [9]. Here we use one of the wafers (D2396) used in that work, [9], the structure and performance of which are described in detail elsewhere [12]. Briefly, the active regions at $\lambda = 8.1$ μm were chosen to be of the so-called "three-well vertical transition" type [13] (see Fig. 1). Radiation is generated by electrons undergoing intersubband transitions between levels 3 and 2. The lasers were processed as deep etched ridges about 10–14-μm wide and were cleaved to lengths of 3.75 mm.

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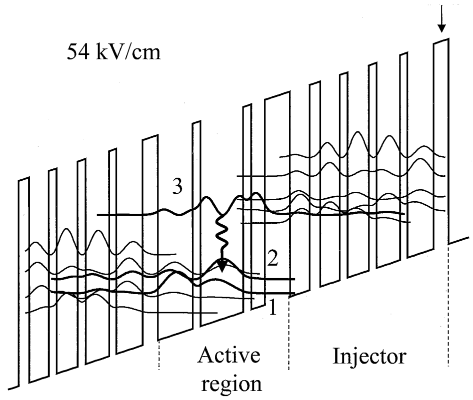

Fig. 1. Conduction band diagram and moduli squared of the wave functions of the QC laser active region designed for emission at $\lambda = 8.1$ μm, sandwiched between two injectors. The layer thickness for one stage of injector and active region in nanometers from right to left starting from the barrier indicated by an arrow are: $\mathbf{2.3}/4.0/\mathbf{1.1}/3.6/\mathbf{1.2}/3.2/\mathbf{1.2}/3.0/\mathbf{1.6}/3.0/\mathbf{3.8}/2.1/\mathbf{1.2}/6.5/\mathbf{1.2}/5.3$. AlInAs layers are in bold. The moduli squared of the wavefunctions involved in the laser emission are indicated by thick lines and are labeled 1, 2, 3.

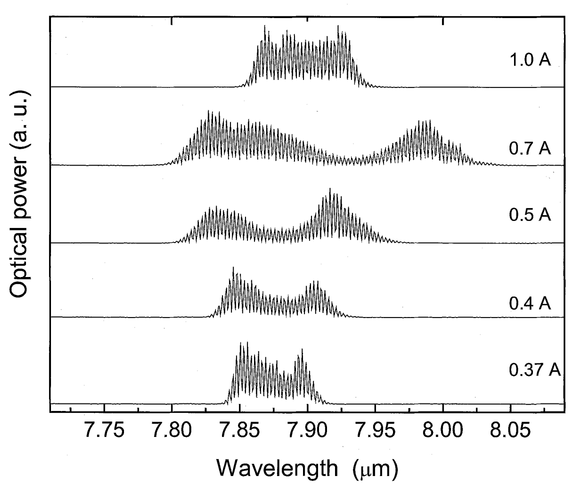

Fig. 2. Laser spectra of one device from wafer D2396 operating in CW at $T = 15$ K at different bias currents as indicated.

The optical confinement was optimized by a so-called "plasmon enhanced" waveguide [14]. The lasers were mounted inside a helium flow cryostat and all measurements were performed at cryogenic temperature ($T = 15$ K) and under an applied dc bias. The optical spectra were measured with a Nicolet fast Fourier transform (FFT) IR spectrometer and a deuterated triglycine sulfate (DTGS) detector. The time dependence of the integrated optical signal was measured with a fast quantum-well IR photodetector (QWIP) with a 40-GHz cutoff frequency [15].

Fig. 2 shows optical spectra of a 3.75-mm-long QC laser operating under applied dc bias at $T = 15$ K. From a current slightly above threshold ($I_{\rm th} \approx 0.35$ A) and over a wide range of the dc bias, the laser emits a broad spectrum, consisting of a large number of Fabry–Perot modes, and with a characteristic oscillatory envelope indicative of pulsed emission undergoing strong self-phase modulation [9]. The photocurrent spectrum, measured with a QWIP and an electronic spectrum analyzer, exhibits a strong, stable peak at the cavity round-trip frequency,

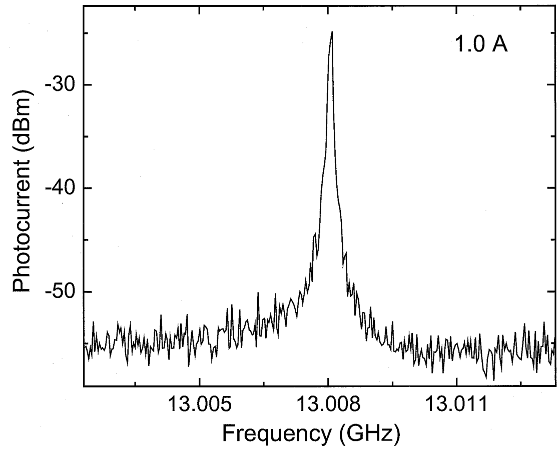

Fig. 3. Photocurrent spectrum of the QWIP at a laser bias current of $I = 1.0$ A.

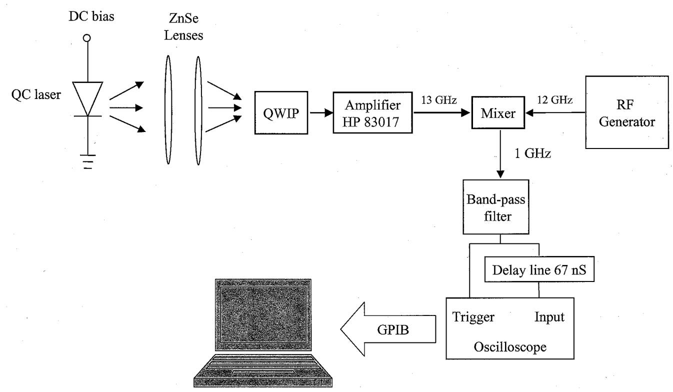

Fig. 4. Schematic of the experimental setup for the time-resolved study of pulse emission in QC lasers. The high-frequency photocurrent signal of the QWIP is downconverted to frequencies around 1 GHz by mixing the former with the signal from an RF generator. The time dependence of the pulsed emission is then measured with a high-speed oscilloscope.

as shown in Fig. 3. These observations represent direct evidence of self-mode-locking [9].

Fig. 4 shows a schematic of the experimental setup employed for the observation of pulsed emission in the time domain. The measurement method is a conventional heterodyne setup, in which the high-frequency sample signal is downconverted to a lower frequency by mixing with an external reference signal. Here, the high-frequency photocurrent signal from the QWIP is mixed with a reference signal from an RF generator in a MITEQ double-balanced mixer. The results of the mixing are shown in Fig. 5 where the photocurrent signal at a frequency $f = 13.008$ GHz (Fig. 3) is downconverted to a frequency $\cong$1 GHz. Fig. 5 shows the downconverted photocurrent spectra for three different frequencies of the reference signal. As can be seen, the increase of the reference frequency shifts the photocurrent peak to lower frequencies.

Oscilloscope traces of the downconverted QWIP photocurrent are measured with a Tektronix CSA 803 sampling scope as shown in Fig. 4. The photocurrent signal after downconversion to a frequency around 1 GHz is filtered using a bandpass filter with a bandwidth of 0.4 GHz and split between the trigger and sampling inputs of oscilloscope. A delay line of 67 ns is inserted

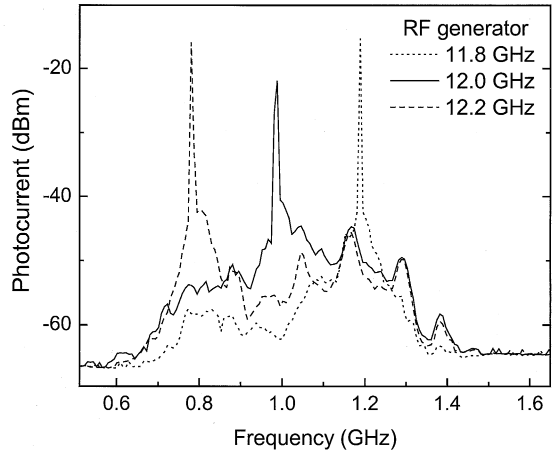

Fig. 5. Downconverted photocurrent spectrum of the QWIP at a laser bias current of $I = 1.0$ A for different mixing frequencies of the RF generator as indicated.

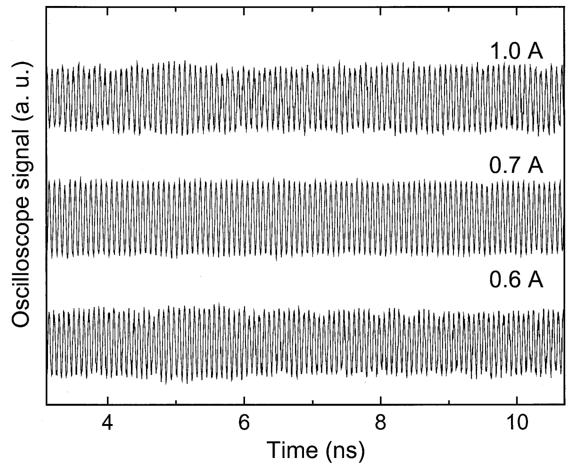

Fig. 7. Oscilloscope traces of pulsed emission of a laser D2396 at various laser bias currents plotted on the actual time scale of pulsed emission, which corresponds to a cavity round-trip frequency of 13.008 GHz.

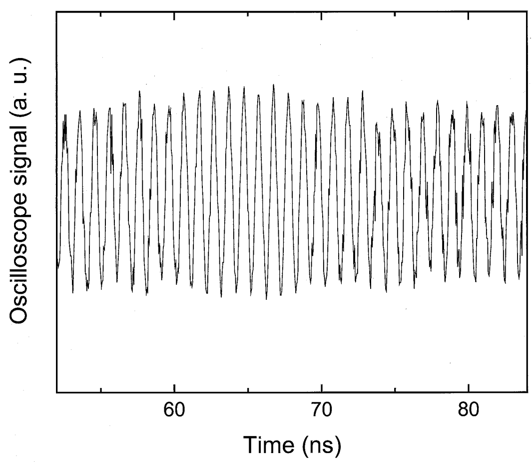

Fig. 6. Oscilloscope trace of the laser pulse emission at a bias current of $I = 1.0$ A (D2396).

before the sampling input of the oscilloscope to compensate for an instrumental delay between the triggering and the start of the data acquisition (37 ns in our scope).

Fig. 6 shows an oscilloscope trace of a QWIP photocurrent signal that has been downconverted from f =13.008 to f_{down} =1.000 GHz using a 12.008-GHz reference signal. The corresponding photocurrent spectra of both the original and downconverted signals are shown in Figs. 3 and 5. The oscilloscope trace shows the stable oscillations of the laser intensity, downconverted to a frequency of 1.000 GHz, corresponding to a cavity round-trip frequency of 13.008 GHz. The narrow bandwidth of our experimental setup filters out all harmonics except for the fundamental one.

The amplitude of the observed oscillations is set by the amplitude of the original mode-locked pulses and the response of the measurement system. Thus, a time dependence of the oscillation amplitude would reflect a pulse drift (in amplitude or phase) with time. For all laser bias currents, however, we observe periodic oscillations with constant amplitude (Fig. 7), which independently confirms the stable nature of the pulsation and hence mode-locking. The pulse train remains stable on a time scale of more than tens of nanoseconds or, equivalently, during emission of several hundred pulses.

III. Enhancement of SHG in Mode-Locked QC Lasers

Intracavity sum-frequency generation and SHG in QC lasers have recently been demonstrated [16]. The nonlinearity arises from intersubband transition in asymmetric coupled QW structures [11]. The optical nonlinearity can be incorporated within the active regions of the QC laser by suitable design of the electronic states or by adding separate multiple QWs. Here we demonstrate SHG in structures of the former type, which have active regions similar to those of self-mode-locked QC lasers [9].

The power of the SHG signal is proportional to the square of the fundamental power. The transition to mode-locking results in a significant increase of the intracavity peak power at the fundamental wavelength, which in turn should also lead to a pronounced increase in the second-harmonic power.

The QC lasers used in this experiment are also based on the "three-well vertical" transition design of the active region. [16] Fig. 8 shows part of the conduction band diagram structure of this laser with energy levels and the moduli of the wavefunctions squared. The laser light is emitted by electrons undergoing transitions between levels 3 and 2. Two sets of resonant transitions for SHG exist in this structure—one for the level triplet 3-4-5 and another for triplet 2-3-4.

The laser processing, mounting, and measurements of the fundamental emission are analogous to the ones described in Section II. The optical spectra of the SHG signal were measured with a Nicolet FFT IR spectrometer in a fast scan mode equipped with a liquid-nitrogen-cooled calibrated InSb detector. A quartz filter was placed before the InSb detector to block the fundamental laser signal. The integrated laser output power was

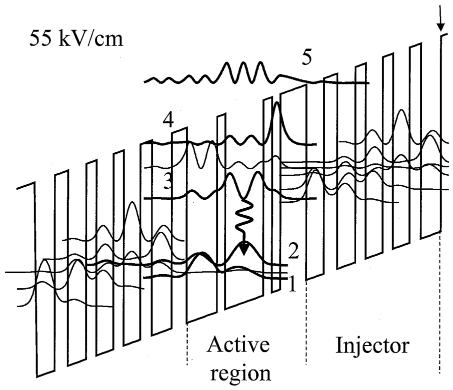

Fig. 8. Conduction band diagram of one active region sandwiched between two injectors of wafer D2882. The laser transition is between levels 3 and 2 and is shown by the wavy arrow. A resonant nonlinearity for intracavity SHG results from two cascades of intersubband transitions 2-3-4 and 3-4-5. The layer thickness in nanometers of one injector and active region are from right to left starting from the barrier indicated by the arrow: **2.6**/3.5/**2.0**/2.9/**1.8**/3.0/**1.8**/3.2/**2.3**/3.1/**4.5**/1.5/**1.5**/6.7/**1.4**/5.3. AlInAs layers are in bold. The moduli square of the essential wavefunctions are also shown and labeled 1–5.

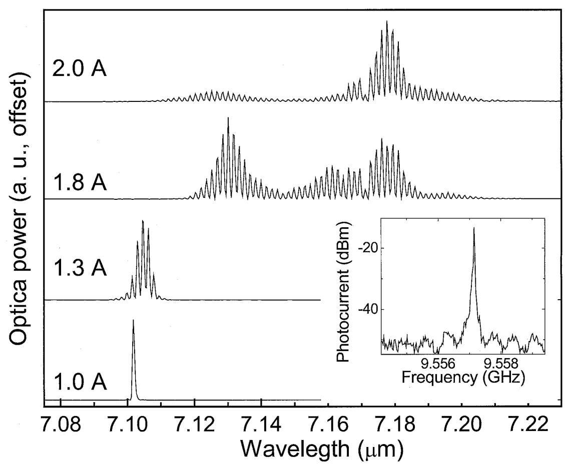

Fig. 9. Laser spectra of one device of D2882 operating in CW at $T \approx 20$ K and at different bias currents. Inset: photocurrent spectrum of the QWIP at a laser bias current of $I = 2.0$ A.

measured with a calibrated thermal detector and the SHG power was calculated from the corresponding spectra.[1]

Fig. 9 shows a few optical spectra of a 4.5-mm-long laser at different dc bias currents. At low bias the laser is single mode; an increase of the current results in the appearance of several modes at $I = 1.3$ A, and a pronounced change of the spectra occurs at $I = 1.8$ A with the simultaneous appearance of many modes, an oscillatory envelope, and a pronounced redshift. The latter change in the emission spectra is accompanied by a transition from CW emission to pulsed emission. In fact, the analysis of the laser output with the QWIP and a spectrum analyzer reveals a strong stable resonance at a cavity round-trip frequency of $f = 9.557$ GHz (inset in Fig. 9). The oscilloscope traces of the photocurrent after downconversion demonstrate a stable pulse train.

The transition to pulsed emission is triggered by the onset of self-mode-locking at high optical intensities inside the laser cavity. Self-mode-locking in these QC lasers is based on self-focusing and arises from an intensity-dependent refractive index [9]. The nonlinearity of the refractive index is provided by the resonant intersubband transition and it changes sign across the center frequency. Self-mode-locking can only occur when the optical spectra shift to longer wavelengths where the nonlinear refractive index is positive. Indeed, the center of mass of the laser spectra in Fig. 9 shifts to longer wavelengths by $\Delta\lambda \approx 0.06$ μm ($\Delta\nu \approx 0.36$ THz) at the onset of mode-locking. The expected value of wavelength shift $\Delta\nu_{\rm th}$ can be estimated from the width of the intersubband transition $\Delta\nu_0$ [9], [17]. The nonlinear refractive index of the intersubband transition n_2 is given by the following expression [9]:[2]

$$n_2 = \frac{q^2 z_{32}^2 \Delta N}{8 n_0 \varepsilon_0 h} \frac{(\Delta\nu_0)^2(\nu_0 - \nu)}{[(\Delta\nu_0/2)^2 + (\nu_0 - \nu)^2]^2} \frac{1}{I_0^{\rm sat}} \tag{1}$$

where z_{32} is the dipole matrix element of the lasing transition, ΔN is the population inversion per unit volume, n_0 is the linear refractive index, ν_0 and $\Delta\nu_0$ are the center frequency and FWHM of the gain curve, $I_0^{\rm sat}$ is the saturation intensity at $\nu = \nu_0$, and q, ε_0, and h are the unit charge, the vacuum permittivity, and Plank's constant, respectively. The laser will tend to mode-lock at optical frequencies near the positive maximum of the nonlinear refractive index. Thus we can estimate the redshift $\Delta\nu_{\rm th}$ from the maximum of (1), namely by setting $\partial n_2/\partial\nu = 0$, which gives $\Delta\nu_{\rm th} \cong \Delta\nu_0/(2\sqrt{3}) = 0.87$ THz for a typical width of the transition of $\Delta\nu_0 \approx 3$ THz. These estimates are in good agreement with the observed shift of $\Delta\nu \approx 0.36$ THz, taking into account the uncertainty of $\Delta\nu_0$ and the approximations used in the above expression for $\Delta\nu_{\rm th}$.

Fig. 10 shows optical spectra of the SHG signal at various laser bias currents. The SHG is a sharp feature superimposed on a smooth background of spontaneous emission from electrons excited into high energy levels and the continuum above the barriers [16].[3] The spectrum of the SHG signal follows that of the laser and changes near the mode-locking transition from single-mode to broad spectral emission shifted to longer wavelength.

Fig. 11 shows high-resolution spectra of the laser and nonlinear optical signals where the latter actually consists of second-harmonic and sum-frequency generation of the individual longitudinal modes of the laser. As a result, the number of resolved modes in the nonlinear optical spectrum

[1]In order to test the precision of this approach, we compared the power of the fundamental laser emission measured with a calibrated detector with the power calculated from the optical spectra measured with the FTIR. Both measurements were in very good agreement.

[2]This expression is based on a two-level approximation. In current devices, the refractive index nonlinearity arises from the intersubband transitions between levels 3-2 and 3-4 and the expression for n_2 is more complicated. Still, the contributions from both transitions are compatible so this expression provides a good estimate of n_2.

[3]The SHG signal is small in these structures because the nonlinear optical element is not optimized and there is no phase matching between the fundamental and nonlinear light modes. Recent work on SHG generation in QC lasers improved the conversion efficiency of the nonlinear optical element and achieved phase matching that enhanced the SHG signal significantly. These optimized lasers, however, cannot be used in our study since they do not emit in CW mode due to higher threshold currents [18].

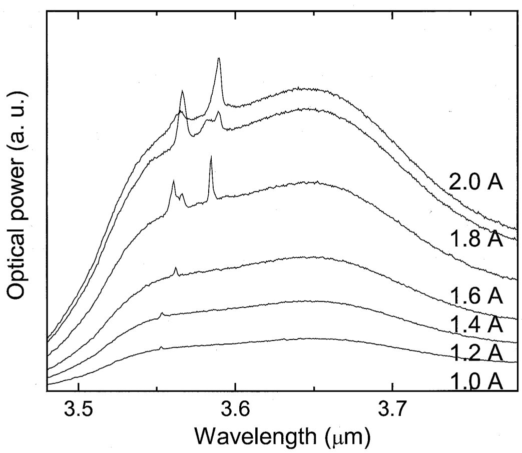

Fig. 10. Short-wavelength spectra of a device of D2882 measured at various laser bias currents. The second-harmonic signal is the sharp feature superimposed on a smooth background of spontaneous emission.

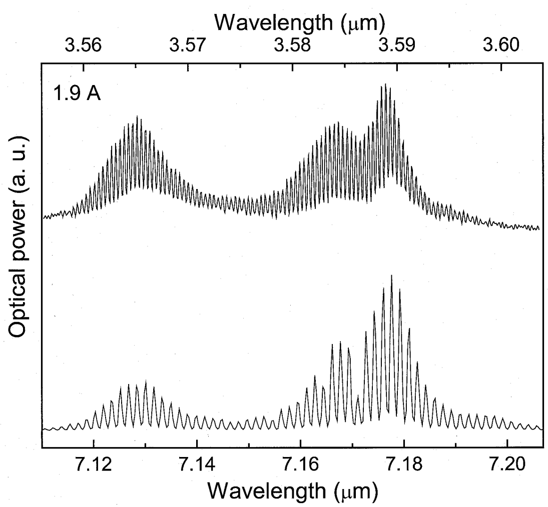

Fig. 11. High-resolution spectra of fundamental (bottom) and second harmonic (top) signals measured at a bias current of $I = 1.9$ A.

is twice the number of modes of the laser spectrum. As the strength of the optical nonlinearity varies only weakly across the laser spectrum all laser modes are expected to interact with each other as long as they overlap spatially and temporally. A laser spectrum with a two-peaked envelop and complete spatial and temporal overlap of all modes would thus lead to a three-peaked envelope in the nonlinear signal, with the third central peak arising from sum-frequency generation of the other two peaks. In the case of laser emission of short pulses undergoing self-phase modulation (SPM), however, the spectral envelope is equally two-peaked, as previously mentioned and discussed in detail elsewhere [9], [19], yet the temporal overlap of the laser modes is reduced. In particular, the two peaks of the spectral envelope are emitted separately in time from the leading and trailing edges of the pulse and thus do not lead to significant sum-frequency generation. This explains the two- rather than three-peaked envelope of the nonlinear spectrum shown in Fig. 11(b) and serves as another strong indication of short-pulse generation in our lasers.

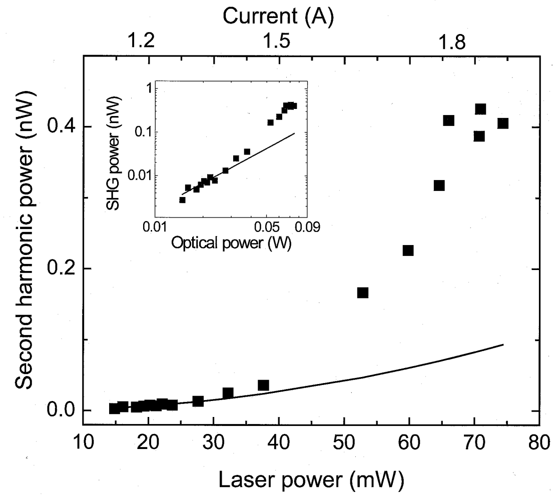

Fig. 12. Power of the SHG signal versus laser power. The solid line is a quadratic least-squares fit to the data at low laser power (data points up to 0.04 W laser power are included in the fit). Inset: power of the second-harmonic signal versus laser power shown on a logarithmic scale.

The power of the SHG signal is plotted versus laser power on linear and logarithmic scales in Fig. 12. When the laser is single mode at low currents (low powers), the SHG signal follows a square dependence on the fundamental power, as shown by the straight line in the inset of Fig. 12. The SHG power starts to deviate from the square dependence at the transition of the laser from CW operation to pulsed behavior at $I \approx 1.4$ A (P ≈ 30 mW) and becomes much higher when the laser emits a stable train of pulses at $I \geq 1.8$ A (P ≥ 65 mW). The power of the SHG signal in the mode-locking regime exceeds by almost a factor of six the power expected for CW emission, as calculated from the difference between the measured value and the extrapolated square dependence at low power (Fig. 12).

The change of the SHG power can be used for an estimate of the QC laser pulse duration. Assuming a Gaussian pulse of width τ (FWHM), the change of the average SHG power is equal to[4]

$$k \approx \sqrt{\frac{2\ln 2}{\pi}}\frac{T}{\tau} \tag{2}$$

where k is the ratio between the SHG signal measured under pulsed conditions and the SHG CW power extrapolated at the same value of the laser power, and T is the cavity round-trip time. Thus, the pulse duration calculated from the enhancement of the SHG is $\tau \approx 12$ ps for a cavity round-trip frequency of $f = 9.557$ GHz ($T = 104$ ps). The pulsed emission with repetition frequency of $f \approx 9.5$ GHz, duration of $\tau \approx 12$ pS, and average power $P \approx 70$ mW results in a peak power $P_p \approx 0.6$ W.

An independent estimate of the pulse duration can be obtained from the time–bandwidth product of optical spectra of the laser. In the presence of SPM, the pulse duration of a Gaussian

[4]At the transition from CW to mode-locking, the pulse peak power is $P_{\rm ml} \cong P_{\rm cw} \times (T/\tau)$, where $P_{\rm cw}$ is the average laser power (or CW laser power), and T and τ are the cavity round-trip time and the pulse duration, respectively. The SHG pulse peak power is $P_{\rm ml}^{2\omega} \cong P_{\rm cw}^{2\omega} \times (T/\tau)^2$, where $P_{\rm cw}^{2\omega}$ is the SHG CW power at the same value of the laser power. We measure the average SHG power, which is given by $\tilde{P}_{\rm ml}^{2\omega} \cong P_{\rm ml}^{2\omega} \times (T/\tau) \cong P_{\rm cw}^{2\omega} \times (T/\tau)$.

pulse τ_p and the rms spectral width $\Delta\nu_{\rm rms}$ are related by the following expression [19]:

$$\tau_p \Delta\nu_{\rm rms} = \frac{\sqrt{2\log 2}}{\pi}\sqrt{1+\frac{4}{3\sqrt{3}}\phi_{\max}^2} \qquad (3)$$

where $\phi_{\max}$ is the nonlinear phase shift corresponding to the pulse peak power. The shape of laser spectra at pulsed emission has two humps with a pronounced dip in the center (see Fig. 9) that is characteristic [19] of a phase shift $\phi_{\max} \approx 3/2$ pi. The largest measured rms width of the spectrum is $\Delta\nu_{\rm rms} \approx 175$ GHz, resulting in $\tau_p \approx 9$ ps, in good agreement with the previous estimate.

In conclusion, we have demonstrated the stability of pulsed emission in self-mode-locked QC lasers. We also observed an enhancement of the intracavity SHG at the transition to self-mode-locking, which results from the high peak power.

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Alexander Soibel received the M.Sc. and Ph.D. degrees in physics from the Weizmann Institute of Science, Israel, in 1995 and 2001, respectively. His master's research concentrated on quantum effects in two-dimensional electron gas (2DEG) and his doctoral work focused on magnetooptical visualization of magnetic transitions and transport currents in High-Tc superconductors.

In 2001, he joined Bell Laboratories, Lucent Technologies, Murray Hill, NJ, as a Postdoctoral Member of the Technical Staff in the Semiconductor Physics Research Department, where he has been involved in research on ultrashort pulse generation in mid-infrared quantum cascade (QC) lasers and on nonlinear optical effects in mode-locked QC lasers. In 2004, he became a Senior Member of Engineering Staff with the Jet Propulsion Laboratory, NASA/Caltech. He has coauthored over 15 papers and has given several invited talks at conferences.

Dr. Soibel is a member of the American Physical Society, the Optical Society of America, the SPIE-International Society for Optical Engineering, and the Materials Research Society. He is the recipient of a Rothschild Fellowship, Israel (2001).

Federico Capasso (M'79–SM'85–F'87) received the Ph.D. degree in physics *(summa cum laude)* from the University of Rome, Rome, Italy, in 1973.

He joined Bell Laboratories first as a Visiting Scientist in 1976 and then as Member of Technical Staff in 1977. He is a Bell Laboratories Fellow and was Physical Research Vice President at Bell Laboratories, Lucent Technologies, Murray Hill, NJ, from 2000 until 2002. From 1997 to 2000, he headed the Semiconductor Physics Research Department and from 1987 to 1997 he was Head of the Quantum Phenomena and Device Research Department. He is currently the Gordon McKay Professor of Applied Physics and Vinton Hayes Senior Research Fellow in Electrical Engineering, Division of Engineering and Applied Sciences, Harvard University, Cambridge, MA. He is internationally recognized for his basic and applied research on bandgap engineering and on atomically engineered semiconductor materials and devices and he is a co-inventor of the quantum cascade laser. His work has opened up new areas of investigation in semiconductor science, mesoscopic physics, nonlinear optics, electronics, and photonics. He has coauthored over 300 papers, edited four volumes, and given over 150 invited talks at conferences. He holds over 35 U.S. patents and over 50 foreign patents. He is a member of the editorial boards of the *Proceedings of the National Academy of Sciences* and was previously on the editorial boards of *Semiconductor Science and Technology, Il Nuovo Cimento, and Applied Physics Letters*.

Dr. Capasso is a member of the National Academy of Sciences, the National Academy of Engineering, and a fellow of the American Academy of Arts and Sciences. He was the recipient of the R. Wood Prize of the Optical Society of America, the Duddell Medal of the Institute of Physics, the Willis Lamb Medal for Quantum Optics and Laser Physics, the John Price Wetherill Medal of the Franklin Institute, the Rank Prize for Optoelectronics, the W. Streifer IEEE LEOS Award, the Materials Research Society Medal, the Newcomb Cleveland Prize of the American Association for the Advancement of Science, the LMVH "Vinci of Excellence" Prize, the Heinrich Welker Memorial Medal, the Gallium Arsenide Symposium Award, the New York Academy of Sciences Award, the IEEE David Sarnoff Award in Electronics, the Capitolium Prize, the Alessandro Volta Medal from the University of Pavia, the Seal of the University of Bari, a Popular Science Award, an Electronics Letter Best Paper Prize, the AT&T Bell Laboratories Distinguished Member of Technical Staff Award, and the Award of Excellence of the Society for Technical Communications. He is an honorary member of the Franklin Institute and a fellow of the Optical Society of America, the American Physical Society, the Institute of Physics (London), the American Association for the Advancement of Science, and SPIE. He is listed in the database of most cited scientists of the Institute for Scientific Infomation (ISI).

Claire Gmachl (S'94–A'95–SM'00) received the M.Sc. degree in physics from the University of Innsbruck, Austria, and the Ph.D. degree (sub auspicies praesidentis) in electrical engineering from the Technical University of Vienna, Austria, in 1995. Her studies focused on integrated optical modulators and tunable surface-emitting lasers in the near infrared.

In 1996, she joined Bell Laboratories, Lucent Technologies, Murray Hill, NJ, as Post- Doctoral Member of Technical Staff in the Quantum Phenomena and Device Research Department, to work on quantum cascade laser devices and microcavity lasers. In March 1998 she became a Member of Technical Staff in the Semiconductor Physics Research Department, working on quantum cascade laser devices and applications and on intersubband photonic devices, and has been named a Distinguished Member of Staff in 2002. In September 2003, Dr. Gmachl joined Princeton University as an Associate Professor in the Department for Electrical Engineering. Dr. Gmachl has co-authored more than 130 papers, has given more than 30 invited talks at international meetings, and holds 15 patents.

Dr. Gmachl is a member of the 2002 TR100 and a 2002/03 IEEE/LEOS Distinguished Lecturer. She is also a co-recipient of the "The Snell Premium" award of the IEE, UK, 2003, and the 2000 "NASA Group Achievement Award", and a recipient of the 1996 "Solid State Physics Award" of the Austrian Physical Society, and the "1995 Christian Doppler Award" for engineering sciences including environmental sciences, Austria. She is senior member of the IEEE and Laser and Electro-Optics Society, and a member of the American Association for the Advancement of Science, the American Physical Society, the Austrian Physical Society, the New York Academy of Science, the Optical Society of America, the SPIE-International Society for Optical Engineering, and the Materials Research Society.

Milton L. Peabody received the B.S. degree from University of Maine, Orono, in 1980.

In February 1980, he joined Bell Laboratories, Murray Hill, NJ, where he has been in the Advanced Lithography Research area, has been involved with the Electron Beam Exposure System IV for opticial photomask lithography, and where he was a member of the Photomask Development Shop in the inspection, repair, and metrology areas. In the 1990s, he was a member of the SCALPEL project, electron beam lithography system, involved in wet silicon deep etching and thin metal low stress films for the electron beam membrane mask. In 2000, he joined the Tuned Frequency Resonator group to do trench etching for the membrane release in this device. Since 2002, he has been involved in semiconductor laser research, working on the processing of the quantum cascade laser devices.

A. Michael Sergent has been with Bell Laboratories, Murray Hill, NJ, since July 1960. He has been in the Semiconductor Research area since the latter part of 1967. He has worked on the luminescence properties of the CdS and ZnSe materials systems and has also performed *C–V*, *C–T*, and deep-level transient spectroscopy measurements on GaAs. Since the early 1990s, he has been involved with semiconductor laser research, working on the electroabsorption modulated laser and most recently the quantum cascade laser. Most of his work in this endeavor revolved around the cleaving and mounting of the devices.

Roberto Paiella (S'96–M'98) was born in Milan, Italy, on December 11, 1970. He received the B.S. and M.S. degrees in electrical engineering from Columbia University, New York, NY, in 1993 and 1994, respectively, and the Ph.D. degree in applied physics from the California Institute of Technology, Pasadena, in 1998. His thesis research focused on the nonlinear optical properties of semiconductor optical amplifiers and their application to wavelength conversion.

In 1998, he joined Bell Laboratories, Lucent Technologies, Murray Hill, NJ, as a Postdoctoral Member of the Technical Staff in the Semiconductor Physics Research Department, where he worked on high-speed mid-infrared quantum cascade lasers for ultrafast pulse generation as well as optical wireless communications. In 2000, he became a Member of the Technical Staff of the Semiconductor Photonics Research Department, Bell Laboratories, which shortly thereafter was spun off as part of Agere Systems. There, he was involved in research and development work on InP photonic integrated circuits for all-optical signal processing and on high-temperature diode lasers. In September 2003, he joined Boston University, Boston, MA, as an Assistant Professor of Electrical Engineering.

Dr. Paiella is a member of the IEEE Laser and Electro-Optics Society, the Optical Society of America, Tau Beta Pi, and Eta Kappa Nu.

Deborah L. Sivco received the B.A. degree in chemistry from Rutgers University, New Brunswick, NJ, in 1980, and the M.S. degree in materials science from Steven Institute of Technology, Hoboken, NJ, in 1988. In 1981, she joined Bell Laboratories, Lucent Technologies, Murray Hill, NJ, where she is currently a Member of Technical Staff in the Semiconductor Research Laboratory. She has been involved with molecular beam epitaxy growth of III-V compounds since 1981, and has performed the crystal growth of GaAs-AlGaAs and InGaAs-InAlAs heterostructures for field-effect transistors, resonant tunneling transistors, bipolar transistors, double-heterostructure lasers, and detectors. She recently prepared the world's first quantum-cascade laser, designed by Faist *et al.*, using bandgap engineering. She has co-authored more than 170 journal papers and holds fifteen patents.

Ms. Sivco was co-recipient of the Newcomb Cleveland Prize AAAS in 1994, the British Electronics Letters Premium Award in 1995, and a Technology of the Year Award from *Industry Week* magazine in 1996.

Alfred Y. Cho (F'81) was born in Beijing, China, in 1937. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Illinois at Urbana-Champaign in 1960, 1961, and 1968, respectively. In 1968, he joined Bell Laboratories, Murray Hill, NJ, as a Member of Technical Staff and was promoted to Department Head in 1984. He was named Director of the Materials Processing Research Laboratory in 1987, and assumed his present position as Semiconductor Research Vice President in 1990. He is also an Adjunct Professor at the University of Illinois at Urbana-Champaign, a member of the Board of Directors of Riber Inc., and a member of the Board of Trustees of the College of New Jersey at Trenton. He has made seminal contributions to materials science and physical electronics through his pioneering development of the molecular beam epitaxy (MBE) crystal growth process. His work has bridged many disciplines ranging from fundamental quantum physics through epitaxial crystal growth, to device fabrication and testing. He laid the foundation for the MBE process in the early 1970s through the use of *in situ* monitoring techniques during epitaxial growth of GaAs. He was the first to observe the two-dimensional high- energy electron diffraction pattern of GaAs crystal growth and the smoothing of the crystal surface, which ultimately formed the basis for successful growth of MBE materials for bandgap engineering, which are not found in nature, some being unique to MBE. In 1971, he fabricated the first MBE superlattice with AlGaAs–GaAs and in 1974 created the first MBE microwave device, a GaAs voltage varactor. Among other III-V devices he has developed using MBE are the IMPATT diode (1974), field-effect transistors operating at microwave frequencies (1976), MBE double-heterostructure injection lasers operating continuously at room temperature (1976), low-noise mixer diodes used in radio astronomy (1977), and heterostructure devices such as tunneling transistors based on bandgap engineering (1984). He also demonstrated the first vertical-cavity surface-emitting lasers (VCSELs) operating CW at room temperature in 1989. More recently (1994), he and coworkers demonstrated a fundamentally new type of laser which is a unipolar intersubband semiconductor laser called the quantum cascade laser. He has authored over 566 papers in surface physics, crystal growth, and device physics and performance. He holds 73 patents on crystal growth and semiconductor devices related to MBE.

Dr. Cho is a fellow of the American Physical Society, and the American Academy of Arts and Sciences. He is a member of the U. S. National Academy of Engineering, the National Academy of Sciences, the Third World Academia of Sciences, the Academia Sinica, the Chinese Academy of Sciences, and the American Philosophical Society. He is a recipient of the Electronics Division Award of the Electrochemical Society (1977), the American Physical Society International Prize for New Materials (1982), the IEEE Morris N. Liebmann Award (1982), the GaAs Symposium Award—Ford (1986), the Heinrich Welker Medal—Siemens (1986), the Solid State Science and Technology Medal of the Electrochemical Society (1987), the World Materials Congress Award of ASM International (1988), the Gaede-Langmuir Award of the American Vacuum Society (1988), the Industrial Research Institute Achievement Award of the Industrial Research Institute, Inc. (1988), the New Jersey Governor's Thomas Alva Edison Science Award (1990), the International Crystal Growth Award of the American Association for Crystal Growth (1990), the Asian American Corporate Achievement Award (1992), AT&T Bell Labs Fellow Award (1992), the National Medal of Science, presented by President Clinton (1993), the Newcomb Cleveland Prize of the American Association for the Advancement of Science (1993–1994), the IEEE Medal of Honor (1994), the Materials Research Society Von Hippel Award (1994), The Elliott Cresson Medal of the Franklin Institute (1995), the Computer and Communications Prize of the C & C Foundation, Japan (1995), the New Jersey Inventors Hall of Fame (1997), the Willis E. Lamb Medal for Laser Physics (2000), the University of Illinois Alumni Achievement Award (2000), the IEEE Millennium Medal (2000), Honorary Doctor of Science Degree, City University of Hong Kong (2000), and the Honorary Doctor of Science, Hong Kong Baptist University (2001).

H. C. Liu received the Ph.D. degree in applied physics from the University of Pittsburgh, Pittsburgh, PA, in 1987 as an Andrew Mellon Predoctoral Fellow.

He is currently the Quantum Devices Group Leader with the Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, ON. He has authored or coauthored over 240 refereed journal articles (with about 80 as the first or sole author) and given approximately 50 invited talks at international conferences. He holds over a dozen patents.

Dr. Liu was the recipient of the Herzberg Medal from the Canadian Association of Physicists in 2000 and the Bessel Award from the Alexander von Humboldt Foundation in 2001.