Active Mode Locking of Broadband Quantum Cascade Lasers

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***Abstract*—Active mode locking in broadband quantum cascade (QC) lasers with a repetition rate of about 14.3 GHz has been achieved through the modulation of the laser bias current. At low driving currents, the active mode locking in broadband QC lasers resembles the active mode locking in single-wavelength QC lasers, while at high driving currents, the mode locking properties are governed by the broad spectral gain of these lasers. At high bias currents, the active modulation excites Fabry–Perot modes across the entire gain spectrum from 6.7 to 7.4 μm, with clear evidence of mode locking. The spectral width of the optical gain in the broadband QC lasers exceeds 2 THz and indicates the potential for generating subpicosecond pulses.**

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

I. INTRODUCTION

BROADBAND lasers are of particular interest for ultrashort pulse generation based on active and passive mode locking [1]. A mid-infrared (IR) broadband quantum cascade (QC) laser emitting in pulsed mode from 6 to 8 μm has recently been demonstrated [2] and subsequent optimization of the laser design resulted in broadband continuous wave (CW) emission at wavelengths spanning the range from 6.7 to 7.4 μm [3]. The mid-IR spectral region is scientifically and technologically important for applications such as chemical and biological sensing [4].

Active and passive mode locking in conventional, single-wavelength QC lasers have recently been observed [5], [6]. There is significant interest in the demonstration of mode locking in broadband QC lasers. In these devices, laser action occurs in active regions designed for emission at different wavelengths; thus, the gain spectrum is inhomogeneously broadened. The broad spectral gain of these lasers is expected to shorten the pulse duration below picoseconds, and, therefore, leading to higher peak optical power, which is important for nonlinear spectroscopy. Furthermore, mode locking in inhomogeneously broadened lasers, in particularly in intersubband lasers where all carrier relaxation times are very short, is not yet well understood. Recent work by Lu *et al.* indicates that active mode locking in inhomogeneously broadened lasers depends strongly on the group velocity dispersion (GVD) in contrast to active mode locking in homogeneously broadened lasers [7]. The negative GVD in actively mode-locked inhomogeneously broadened lasers is required to compensate for the effects of self-phase modulation and to limit the spectral width of the optical pulse in order to avoid instabilities, such as pulse breakup.

In this paper, we demonstrate active mode locking of broadband QC lasers by modulation of the laser drive current at frequencies close to the cavity round-trip frequency. The active current modulation brings above threshold hundreds of Fabry–Perot modes and changes laser operation from a CW emission to a pulsed emission. The spectral response of the lasers was found to be strongly dependent on the dc laser bias, and on the modulation amplitude and frequency. The spectral width of the optical emission in the actively mode-locked broadband QC lasers exceeds $\Delta\nu > 2$ THz, which is sufficient for the generation of the subpicosecond pulses.

II. DESIGN OF GAIN SPECTRUM

The design of the lasers has previously been discussed in [3]. In short, the QC laser consists of 35 stages with active regions centered at different emission wavelengths [2]. All active regions were chosen to be of the so-called “three-well vertical-transition” type [Fig. 1(a)] with center wavelengths spanning the range from 6.9 to 7.9 μm [Fig. 1(b)]. The number of stages at each wavelength was chosen to compensate for optical loss variations with wavelength and to achieve a sufficiently flat net modal gain spectrum [3].

The lasers were processed as deep as 10–14-μm-wide etched ridges with 4-μm-thick chalcogenide glass ($\mathrm{Ge}_{0.25}\mathrm{Se}_{0.75}$) insulating coating that covers the ridge sides to allow metallic interconnection between the top contact and the bonding pad.

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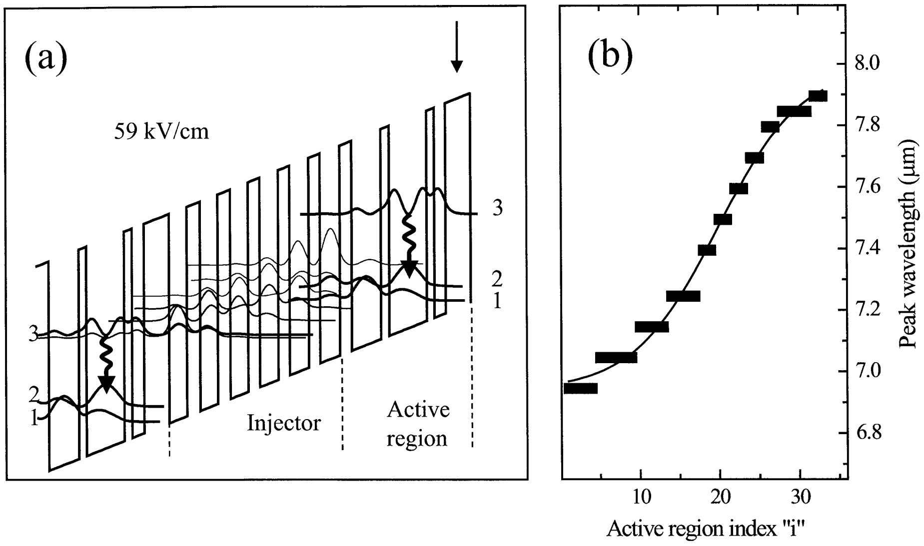

Fig. 1. (a) Conduction band diagram of two active regions of a broadband QC laser designed for the emission at 7.25 μm (right) and 7.40 μm (left) and the intermediate injector. The layer thicknesses in nanometers are, from right to left starting from the injection barrier (indicated by an arrow): **4.2**/1.9/**1.3**/6.3/**1.4**/4.9/**2.0**/3.3/**1.9**/3.2/**1.9**/3.1/**2.0**/3.0/**2.1**/3.0/**2.2**/3.0/**4.2**/2.0/**1.3**/6.3/**1.3**/5.0/**2.0**. AlInAs layers are in bold. The moduli squared of the wavefunctions involved in the laser emission are shown with thick lines. (b) Calculated peak gain wavelength versus active region index.

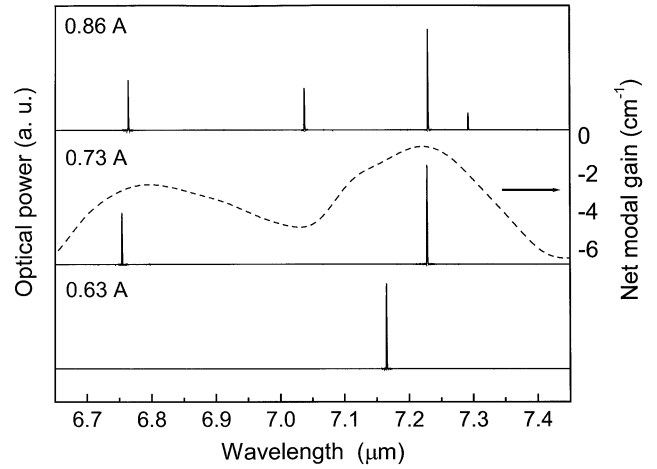

Fig. 2. Laser spectra of the broadband QC laser (sample D2813) operating CW at $T = 20$ K at different bias currents as indicated. The gain spectrum below threshold calculated from the luminescence spectrum is shown by a dash line.

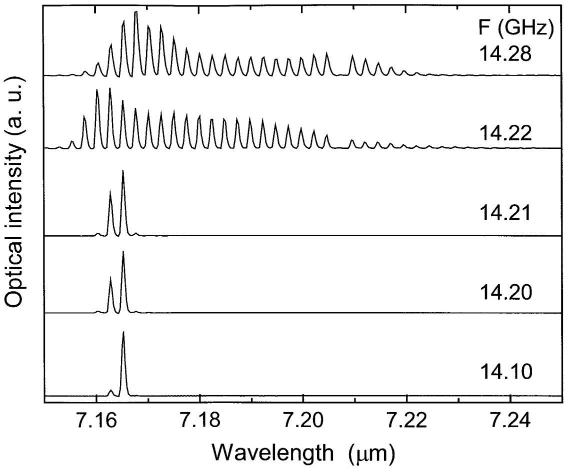

Fig. 3. Optical spectra of the actively mode-locked broadband QC laser at constant dc laser bias $I = 0.63$ A and temperature $T = 20$ K for different values of the RF modulation frequency as indicated. The RF power is $P_{\rm rf} = 30$ dBm.

We chose to replace the more common thin Si_3N_4 insulating coating with thick $Ge_{0.25}Se_{0.75}$ coating in order to reduce chip parasitic capacitance and achieve more efficient gain modulation [5]. The lasers were mounted inside a helium flow cryostat and all measurements were performed at cryogenic temperature ($T = 20$ K). In order to minimize the package parasitics, the lasers were bonded to a 50-Ω microstrip line connected to a cryogenic semirigid cable.

Fig. 2 shows the optical spectra of the D2813 laser operating in CW at different values of operating current, where the optical spectrum at $I = 0.73$ A (middle) is shown together with the net modal gain measured below threshold. The net modal gain was calculated from the subthreshold electroluminescence using the method developed by Hakki and Paoli [8]. The lasers have a measured net modal gain ripple of only about 4 cm^{-1} over the spectral range from 6.7 to 7.4 μm (Fig. 2, middle). At currents slightly above the threshold current $I_{\rm th} \approx 0.6$ A, the laser is single mode at the position of peak gain. The increase of the current to $I = 0.73$ A results in the appearance of the second mode at the other maximum of the gain spectrum. As the current is further increased, additional modes appear across the entire gain spectra.

Active mode locking was achieved by driving the laser with an RF signal from a low-phase-noise signal generator followed by a high-speed amplifier. A bias tee was inserted at the input connector of the cryostat to combine the RF modulation and laser dc bias current. The maximum power of the RF modulation was 30 dBm after the amplifier, but we estimate the power actually reaching the laser to be significantly lower due to a mismatch between the 50-Ω microstrip line and the laser bonding and packaging. The optical spectra were measured with a Nicolet fast Fourier transform infrared spectrometer (FTIR) and a deuterated triglycine sulfate (DTGS) detector. The high-frequency photocurrent signal was measured with

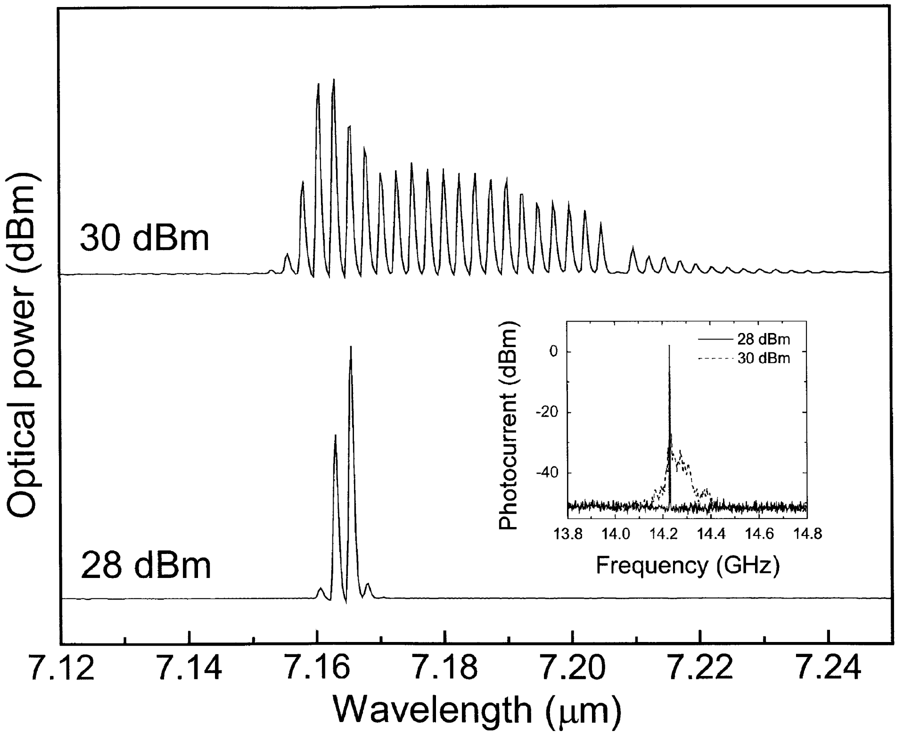

Fig. 4. Optical spectra of the broadband QC laser output at constant dc laser bias $I = 0.63$ A and temperature $T = 20$ K for an RF modulation frequency $f = 14.220$ GHz. The RF power ($P_{\rm rf}$) is 28 dBm (bottom) and 30 dBm (top). Inset: The corresponding photocurrent spectra of the laser output at $I = 0.63$ A measured with the QWIP for various powers of RF modulation, as indicated.

a fast quantum-well infrared photodetector [9] (QWIP) with 40-GHz cutoff frequency[1] followed by a high-speed amplifier and electrical spectrum analyzer.

III. LOW-CURRENT REGIME

The optical spectra of an actively mode-locked 3.2-mm-long broadband QC laser (D2813) are shown in Fig. 3 at various RF modulation frequencies. The RF modulation power is kept constant at $P = 30$ dBm and the laser dc bias is $I = 0.63$ A. In the absence of any modulation the laser emits CW at $\lambda \approx 7.16$ μm (Fig. 2, bottom). The active current modulation transfers the energy from the lasing modes to their neighbors and brings them above threshold [5]. As the modulation frequency is tuned to the range of cavity round-trip frequencies the number of excited modes grows, reaching a maximum in the frequency interval f = 14.22–14.28 GHz.

Direct evidence of active mode locking follows from an analysis of the laser emission with a fast QWIP [9] and an electrical spectrum analyzer. The spectra of the QWIP photocurrent are shown in the inset to Fig. 4 for an actively mode-locked QC laser at a dc bias $I = 0.63$ A, RF frequency $f = 14.220$ GHz, and for two RF powers of $P = 28$ dBm and $P = 30$ dBm. The corresponding optical spectra are shown in Fig. 4. The peak in the photocurrent results from the laser pulse emission at the cavity round-trip frequency. The photocurrent peak broadens significantly when the number of the excited modes increases with RF power. This broadening apparently indicates an incomplete phase-locking of the excited modes that results in the fluctuations of the pulse properties such as the amplitude, pulse duration, and repetition frequency.

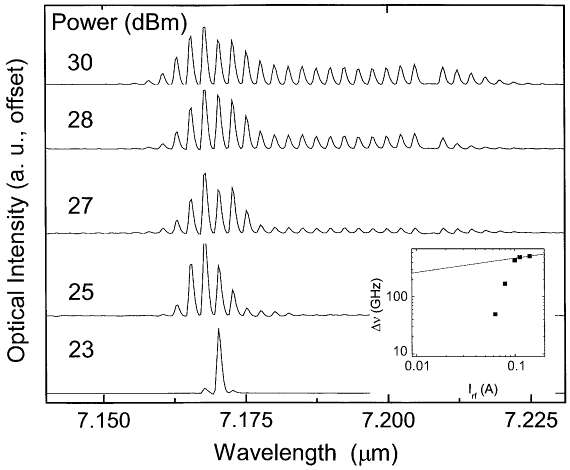

Fig. 5. Optical spectra of the broadband QC laser output at constant dc laser bias $I = 0.63$ A and temperature $T = 20$ K for different values of the RF power. The RF modulation frequency is $f = 14.27$ GHz. Inset: Spectral width of the actively mode-locked broadband QC laser output measured with FTIR plotted on a logarithmic scale versus RF modulation current. The dc laser bias $I = 0.63$ A, the temperature $T = 20$ K, and the modulation frequency $f = 14.27$ GHz. The straight line shows the theoretically predicted dependence of the spectral width on the RF power, $\Delta\nu \sim I_{\rm rf}^{0.25}$.

The dependence of the spectral response on the RF power is shown in Fig. 5 at a laser bias current of $I = 0.63$ A and modulation frequency of $f = 14.27$ GHz. When the RF power $P \leq 23$ dBm, the active modulation results only in the excitation of two weak neighboring modes or RF sidebands. A small increase of RF power to $P = 25$ dBm causes a significant

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[1] The upper frequency limit of these measurements ($f = 25$ GHz) is set by a cutoff frequency of the electrical spectrum analyzer.

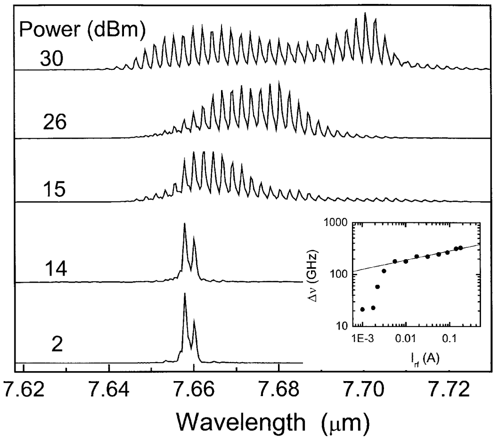

Fig. 6. Optical spectra of a single wavelength QC laser at constant dc laser bias $I = 1.6$ A and temperature $T = 20$ K for different values of the RF power. The RF frequency is $f = 11.46$ GHz. Inset: Spectral width of the actively mode-locked single wavelength QC laser plotted versus RF modulation current. The dc laser bias is $I = 1.3$ A, the temperature is $T = 20$ K, and modulation frequency is $f = 11.486$ GHz. The straight line is a quadratic least square fit to the data at high RF power (data points above $P_{\rm rf} = 2$ dBm or $I_{\rm rf} = 5.6$ mA are included in the fit).

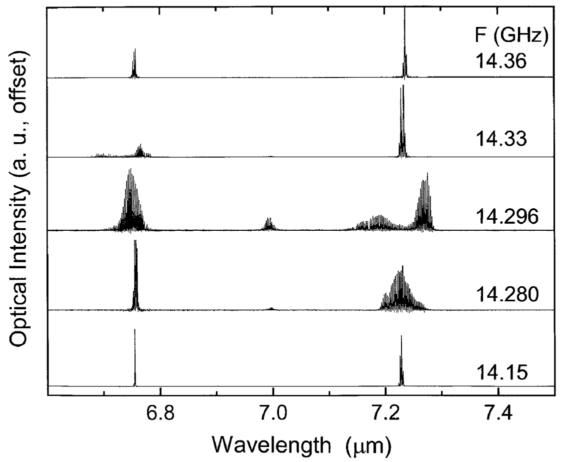

Fig. 7. Optical spectra of the broadband QC laser output at constant dc laser bias $I = 0.73$ A and temperature $T = 20$ K for different values of the RF modulation frequency as indicated. The RF power is $P_{\rm rf} = 30$ dBm.

change of the emitted spectra and an even broader spectrum is observed when $P \geq 28$ dBm.

At low currents, and without RF modulation, the broadband QC laser operates in single mode so that it would be natural to compare the response of the broadband QC laser with the response of a conventional mode-locked QC laser with a gain spectrum peaked at a single wavelength. The active mode locking of conventional QC lasers is described in [5]. Fig. 6 shows optical spectra of the actively mode-locked single wavelength QC laser for the various powers of RF modulation. Similarly, in the single wavelength QC lasers, the spectral response is very weak, below a certain value of RF power (14 dBm here), while a small increase of the RF modulation triggers a considerable change of the emitted spectra and results in the transition from CW to the pulsed emission. After transition to the pulsed emission, the spectral width (and pulse duration) depends weakly on the RF power, as shown in the inset of Fig. 6. A fit to the data at high RF power gives the spectral width $\Delta\nu$ dependence on the RF current $\Delta\nu \sim I_{\rm rf}^{0.18}$ and is in the good agreement with predictions [10], [5] $\Delta\nu \sim I_{\rm rf}^{0.25}$, where $I_{\rm rf} \approx \sqrt{P_{\rm rf}/50\ \Omega}$ is the RF current before the bias tee calculated from the RF power $P_{\rm rf}$, and 50 Ω is the impedance of the bias tee. So, the strong modulation is essential to achieve active mode locking in QC lasers.

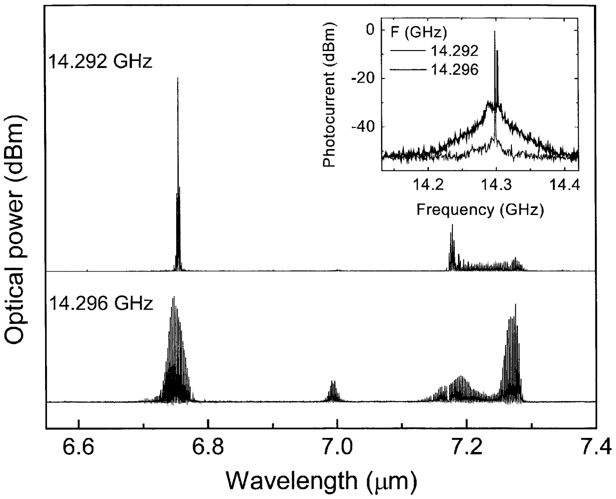

Fig. 8. Optical spectra of the broadband QC laser output at constant dc laser bias $I = 0.73$ A and temperature $T = 20$ K for RF modulation frequencies $f = 14.292$ GHz (top) and $f = 14.296$ GHz (bottom). The RF power is $P_{\rm rf} =$ 30dBm. Inset: Corresponding photocurrent spectra of the laser output measured with the QWIP. The sharp spike is caused by crosstalk between the RF generator and the QWIP, while the broader peak results from the laser pulsed emission at the cavity round-trip frequency.

IV. High-Current Regime

The optical spectra of an actively mode-locked broadband QC laser at higher drive current ($I = 0.73$ A) are shown in Fig. 7 at various frequencies of RF modulation. The power of the RF modulation is kept constant at $P = 30$ dBm. In the absence of any modulation the laser emits CW at two wavelengths: $\lambda \approx 6.75$ μm and $\lambda \approx 7.25$ μm (Fig. 2, middle). As the modulation frequency is tuned to the range of cavity round-trip frequencies ($f \cong 14.2$–14.3 GHz) allowed by the refractive index dispersion, the number of excited modes grows. The actively mode-locked broadband QC laser emits a broad spectrum in two spectral windows centered near the original, unmodulated wavelengths of $\lambda \approx 6.75$ μm and $\lambda \approx 7.25$ μm, which coincide with two maxima of the gain. The envelope of the Fabry–Perot modes centered near $\lambda \approx 7.25$ μm ($f = 14.296$ GHz) has two humps which is characteristic for a strong self-phase modulation resulting from pulse propagation in a medium with intensity-dependent refractive index [11]. This nonlinearity arises from giant optical Kerr effects of the intersubband laser transition as discussed in previous work [6].

The spectrum of the QWIP photocurrent is shown in the inset of Fig. 8 for an actively mode-locked QC laser at a dc bias $I = 0.73$ A and RF power of $P = 30$ dBm for two RF frequencies $f = 14.292$ GHz and $f = 14.296$ GHz. The corresponding optical spectra are shown in Fig. 8. The sharp spike in the photocurrent spectrum arises from crosstalk between the RF generator and detector. The broader peak results from the laser pulse emission at the cavity round-trip frequency. The optical

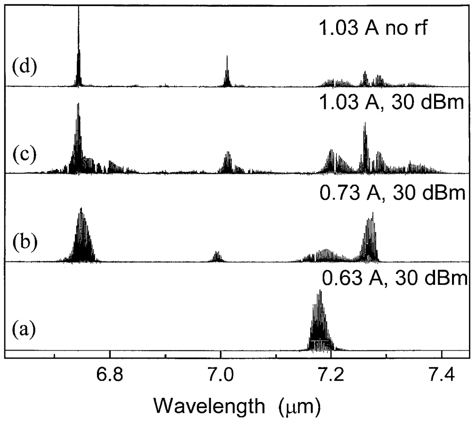

Fig. 9. (a), (b), and (c) Optical spectra of the actively mode-locked broadband QC laser at $T = 20$ K for various dc bias currents. The RF power is 30 dBm and the RF frequency varies slightly with the laser bias current. (d) Optical spectrum of the same broadband QC laser operating in a self-mode locking mode. The laser dc bias and temperature are $I = 1.03$ A and $T = 20$ K, respectively.

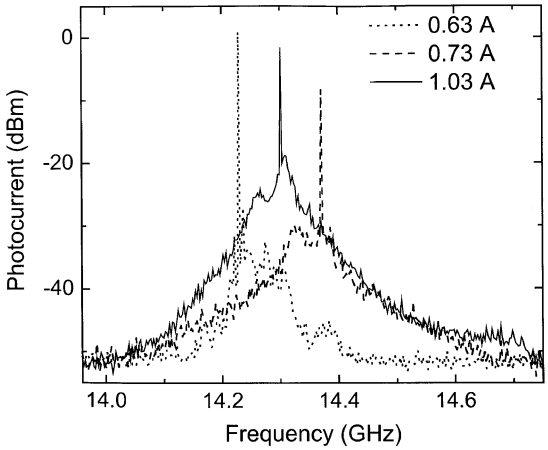

Fig. 10. Photocurrent spectra of the laser output of the actively mode-locked broadband QC laser at $T = 20$ K for various dc bias currents measured with the QWIP. The RF power is 30 dBm and the RF frequency varies slightly with the laser bias current.

and photocurrent spectra of the actively mode-locked broadband QC laser change appreciably with a small variation of the active modulation frequency. The tuning of the latter by 4 MHz from $f = 14.292$ GHz to $f = 14.296$ GHz significantly increases the number of the modes excited by the active modulation, resulting in the higher amplitude of the photocurrent peak, since more modes contribute in phase to the formation of the pulses.

The three bottom graphs in Fig. 9 show the optical spectra of the actively mode-locked broadband QC laser at various dc bias currents. The RF power P is 30 dBm and the modulation frequency is varied with bias current ($f = 14.27$–14.45 GHz) to achieve the respective maximum spectral width. The laser spectral response depends strongly on the laser bias current and reflects the broad spectral gain of the laser and its wavelength dependence. At low drive currents $I = 0.63$ A, the RF modulation brings above threshold only Fabry–Perot modes near the wavelength of the unmodulated laser $\lambda \approx 7.16$ μm. At high dc currents, the active modulation results in the appearance of numerous Fabry–Perot modes across the entire gain spectrum from 6.7 to 7.4 μm. The corresponding photocurrent peaks are shown in Fig. 10. The photocurrent peak broadens with increase of the laser bias current (or laser optical power). This broadening results from poor phase-locking of the modes across the broad spectrum. At high bias, the laser remains in the pulsed mode even after the active current modulation is turned off (top, Fig. 9). This pulsed emission results from a self-mode locking as will be described elsewhere [12].

The common way to measure the duration of ultrashort pulses is through second-order autocorrelation based on the second harmonic generation or on two-photon absorption. These measurements cannot presently be carried out with mode-locked QC lasers due to limited conversion efficiency of nonlinear crystals in the mid-IR and the low pulse peak energy.[2] An estimate of the pulse duration, however, can be obtained from the time–bandwidth product.

In the presence of self-phase modulation (SPM), the pulse duration of a Gaussian pulse τ_p and the root-mean-square (rms) spectral width $\Delta\nu_{\rm rms}$ are related by the following expression [6]:

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

where $\phi_{\rm max}$ is the nonlinear phase shift corresponding to the pulse peak power. At a dc laser bias current $I = 0.63$ A (Fig. 9, bottom), the spectral envelope of the laser output has a Gaussian shape that corresponds to $\phi_{\rm max} \le \pi/2$. The measured rms width of the spectrum at this current is $\Delta\nu_{\rm rms} \approx 131$ GHz, resulting in a pulse duration τ_p in the range $\tau_p \approx 2.8$–4.8 ps, depending on the value of $\phi_{\rm max}$.

Apparently, the shortest pulses can be achieved at high dc laser bias currents where the Fabry–Perot modes across the entire spectral gain width are excited (Fig. 9, $I = 1.03$ A). The latter exceeds $\Delta\nu > 2$ THz pointing out to the possibility of achieving a pulse emission with subpicosecond duration. The spectral envelope at high bias current has a rather unusual shape that may be due to an uncommon pulse shape, effects of SPM, or poor phase-locking of the modes across the broad spectrum. Thus, the estimate of the pulse duration from the spectral width at high currents is inaccurate.

The wide inhomogeneously broadened spectral gain of these lasers prompts a question whether all modes across the entire gain spectrum are phase-locked. For example, at $I = 0.73$ A the laser emits in two spectral windows centered around $\lambda \approx 6.75$ μm and $\lambda \approx 7.25$ μm that are separated from each other. There are no Fabry–Perot modes spaced continuously from one spectral region to the other, so the phase-locking between the two groups of modes centered around the above wavelengths does not hold, since the likelihood that nonlasing modes are locked is negligible given that the power in the modes must be sufficiently high in order for them to lock, while definite phase relations between modes in each group would be maintained.[3]

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[2] Several groups are actively studying nonlinear optical effect in semiconductor structures that have potential for development of the detectors suitable for the second-order autocorrelation measurements in mid-IR. In particular, very promising results were observed for two-photon absorption measurements in quantum dots and in specially designed QWIP.

[3] We attributed the absence of phase-locking of all Fabry–Perot modes across the entire gain spectrum in these lasers to an insufficient flatness of the gain spectrum and to a weakness of the active mode locking modulation.

Such scenario would give rise to the emission of two trains of pulses centered near $\lambda \approx 6.75\ \mu$m and $\lambda \approx 7.25\ \mu$m. Direct evidence of such has recently been observed by us in self-mode-locked broadband QC lasers and will be reported elsewhere [12].

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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, she joined Princeton University as an Associate Professor in the Department for Electrical Engineering. She has coauthored 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 Snell Premium award of the IEE, U.K., 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 a senior member of the 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.

Harold Y. Hwang received the B.S. degree in physics and the B.S. and M.S. degrees in electrical engineering from the Massachusetts Institute of Technology, Cambridge, MA, in 1993, and the Ph.D. degree in physics from Princeton University, Princeton, NJ, in 1997. He studied the physical properties of transition metal oxides, including cuprates and manganites, focusing on magnetotransport as well as spin and lattice dynamics associated with metal-insulator transitions.

In 1997, he joined Bell Laboratories, Lucent Technologies, Murray Hill, NJ, as a Member of Technical Staff in the Materials Physics Research Department. In 2003, he joined the University of Tokyo as an Associate Professor in the Department of Advanced Materials Science, Tokyo, Japan. He is currently studying the electronic structure of thin film complex oxide heterostructures grown by pulsed laser deposition, as well as chalcogenide glass photonics.

Dr. Hwang is a member of the American Physical Society and the Materials Research Society.

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 15 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), theWillis 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.

Christan Jirauschek was born in Karlsruhe, Germany, in 1974. He received his Diploma degree in electrical engineering from the University of Karlsruhe, Karlsruhe, Germany, in 2000.

Since 2002, he has been a Visiting Scientist at the Massachusetts Institute of Technology, Cambridge, and is currently pursuing the Ph.D. degree in electrical engineering. His research interests include dynamics of mode-locked lasers and phase-sensitive nonlinear optics.

Dr. Jirauschek is a member of the German National Merit Foundation, the German Physical Society, and the Optical Society of America.

Franz X. Kärtner (M'89) was born in Cham, Germany, 1961. He received the Diploma and Ph.D. degrees in electrical engineering in 1986 and 1989, respectively, from the Technical University in Munich, Munich, Germany.

From 1991 to 1993, he was a Feodor–Lynen Research Fellow of the Alexander von Humboldt Foundation at Massachusetts Institute of Technology (MIT), Cambridge. From 1993 to 1997, he was a Principal Investigator at the Swiss Federal Institute of Technology (ETH), Zurich, Switzerland. In 1999, after spending a year as a Visiting Assistant Professor at MIT, he joined the Department of Electrical Engineering at the University of Karlsruhe, Karlsruhe, Germany, where he held the Chair for Photonics and Terahertz Technology and headed the High-Frequency and Quantum Electronics Laboratory. In 2001, he joined the Department of Electrical Engineering and Computer Science at MIT. His current research interests are in ultrashort pulse generation, ultrafast phenomena, frequency metrology, and noise in microwave oscillators and optical devices.

Prof. Kärtner is a member of the German Scholarship Foundation, the German Physical Society, and the Optical Society of America.