Quantum cascade lasers (QCLs) offer unparalleled wavelength versatility across the entire mid- to far-infrared spectral range, as well as providing unique modes of operation as a result of the quasi-atomic nature of the intersubband joint density of states. For example, midinfrared broadband QCLs emitting in pulsed mode from 6 to 8 μm have been recently demonstrated, in which a broad gain spectrum is obtained by employing active regions operating at different wavelengths simultaneously. By introducing additional mirror loss in the Fabry–Perot resonator using just a single cleaved facet, with the other mirror formed by wet etching, the laser threshold current is significantly increased and superlinear light-current characteristics are observed. Optical peak powers of several tens of μW are measured at low temperatures. © 2006 American Institute of Physics. [DOI: 10.1063/1.2188371]

Midinfrared emission from intersubband superluminescent light-emitting diodes is reported. We have obtained broadband emission spectra at around 7 μm with a full width at half maximum of ~2 μm, using quantum-cascade-laser active regions designed to emit at 11 different wavelengths simultaneously. By introducing additional mirror loss in the Fabry–Perot resonator using just a single cleaved facet, with the other mirror formed by wet etching, the laser threshold current is significantly increased and superlinear light-current characteristics are observed. Optical peak powers of several tens of μW are measured at low temperatures. © 2006 American Institute of Physics. [DOI: 10.1063/1.2188371]
Perot mirror is replaced by a wet etched facet in order to suppress laser action. From the scanning electron microscopy (SEM) images, we measured the etched facet angle of \( \sim 45 \pm 10^\circ \) and roughness less than 0.5 \( \mu m \), much smaller than the operating wavelengths. Thus our etched facet behaves like a mirror reflecting light into the substrate.

Figure 2 shows the typical low-temperature emission spectra of the investigated laser [Fig. 2(a)] and LED devices [Fig. 2(b)] measured with 0.12 cm\(^{-1}\) resolution using a Bruker IFS 66v/s Fourier transform infrared spectrometer in step scan mode. In order to minimize water vapor absorption, the space between the sample position and the spectrometer was purged with purified air. The laser devices exhibit multiwavelength operation across the designed 6 to 8 \( \mu m \) spectral range. At current densities greater than four times the threshold current, laser action across a continuous band between 6 and 8 \( \mu m \) was observed. The intensity of the laser lines was highly nonuniform and varied by more than ten times, which is undesirable for high spatial resolution applications since it increases the coherence length. On the other hand, the QC LED emits with much more uniform intensity across the 6–8 \( \mu m \) range with peak maximum \( \lambda_m \) at \( \sim 7 \mu m \) and full width at half maximum (FWHM) \( \Delta \lambda \) of \( \sim 1 \mu m \).

The light output \( (L) \) and voltage \( (V) \) versus current density \( (J) \) characteristics of the QC laser and LED devices are represented in Fig. 3. The light was collected from one facet with approximately 30\% efficiency using an off-axis parabolic mirror and measured with a calibrated liquid-nitrogen-cooled HgCdTe detector. The laser device has threshold current density \( J_t=1590 \text{ A/cm}^2 \) at 10 K. The \( L-J \) characteristic comprises three distinct parts: Spontaneous emission, amplified spontaneous emission (ASE), and stimulated emission or lasing. Below \( J=1000 \text{ A/cm}^2 \), the \( L-J \) characteristic shows linear dependence (dashed line in Fig. 3) corresponding to spontaneous luminescence. Between 1000 and 1590 \( \text{A/cm}^2 \), the light intensity increases with current with a superlinear dependence, indicating the amplified emission regime just before lasing. By using the single facet cleaved ridge LED device, we increased the threshold current density to \( J_t=5400 \text{ A/cm}^2 \) at 10 K for the 1.7-mm-long ridges. Since the waveguide losses for the laser and LED devices are the same, we are able to estimate the increase of the mirror loss in our single cleaved facet LED device. The calculated mirror loss for the 2-mm-long laser ridge is \( \sim 6 \text{ cm}^{-1} \), and assuming the waveguide loss for our laser/LED device of about 5 \( \text{cm}^{-1} \), we estimate the increased mirror loss for the 1.7-mm-long single facet LED device of \( \sim 30 \text{ cm}^{-1} \), corresponding to an effective reflection coefficient of \( \sim 0.01\% \) (compared with \( \sim 30\% \) from the cleaved facet). Such a high value for the mirror loss suggests that this approach is very efficient in suppressing the optical feedback and enhancing the ASE contribution before lasing. A further increase of the ridge length to 2.5 mm decreases the threshold current density to \( \sim 4300 \text{ A/cm}^2 \), because of slightly reduced mirror loss. Both 1.7- and 2.5-mm-long devices exhibit superlinear \( L-J \) dependence (Fig. 3), which is clear evidence of superluminescence occurring in our devices. Moreover the optical peak intensity for 2.5-mm-long LED is enhanced by a factor of \( \sim 2.5 \) at \( J=4000 \text{ A/cm}^2 \) (\( \sim 25 \mu W \)) compared with the 1.7-mm-long device (\( \sim 10 \mu W \)). This enhancement does not scale linearly with the ridge length increase because of the presence of the gain, providing additional evidence of the amplified emission observed in our QC LED devices. By analyzing the \( L-J \) dependence for different lengths of QC LEDs, we are able to determine the waveguide loss \( \alpha_w \) and gain coefficient \( g \). The ASE intensity \( I(l) \) from the end of pumped stripe of length \( l \) originating from point-source spontaneous emission \( I_{\text{spont}} \) distributed uniformly along the ridge is

\[
I(l) = \frac{I_{\text{spont}} \exp[(g \cdot J - \alpha_w) l] - 1}{g \cdot J - \alpha_w},
\]

where \( (g \cdot J - \alpha_w) \) is the net modal gain. Using Eq. (1), with the values of waveguide loss \( \alpha_w=5 \text{ cm}^{-1} \) and gain coefficient \( g=4.3 \text{ cm kA}^{-1} \) obtained from experiment, we can estimate the achievable optical peak power, which for a 5-mm-long QC LED device at 4 \text{ kA/cm}^2\text{ can be as high as } \sim 500 \mu W.\text{14}

The effect of variation of the duty cycle and the temperature on the \( L-J \) characteristic of the 1.7-mm-long and 56-\( \mu m \)-wide QC LED ridge is presented in Fig. 4. The increase of either the pulse length or repetition rate leads to an increase of the average output power from the LED device [Fig. 4(a)]. An average power of \( \sim 0.2 \mu W \) was measured for 500-ns-long pulses at 25 kHz repetition rate. However, at the same time, the peak power decreases from \( 20 \mu W \) to \( 15 \mu W \) because of heating of the laser core during the pulse. This heating also suppresses laser generation in the QC LED device at higher duty cycles. Increasing the temperature of the device produces the same effect [Fig. 4(b)], though the output power stays almost the same up to 80 K at current \( I \).
< 4 A, and only at very high current I > 4 A does the additional heating of the sample during the pulse decrease the superluminescence efficiency. Increasing the temperature to T > 80 K significantly reduces the light intensity. At T = 150 K, the output power from the broadband QC LED device is reduced by about a factor of 2 compared with the value at 80 K.\(^{15}\)

Figure 5 shows the emission spectra of the 1.7-mm-long LED device at various current densities for 100 ns [Fig. 5(a)] and 300 ns [Fig. 5(b)] pulse widths and 25 kHz repetition rate. Because of the inhomogeneous broadening of the gain spectrum, a narrowing of the emission spectra under increased current is not expected, as would be observed in homogeneously broadened systems. However because the active regions emitting at central wavelengths (around 7 μm) are placed close to the maximum of the optical mode inside the waveguide, the amplification of these wavelengths is more efficient. This causes narrowing of the superluminescence spectrum in the broadband QC LED with increasing current [see inset of Fig. 5(b)]. The spectral line width decreases from Δλ = 1.9 μm at I = 2 A to Δλ = 0.6 μm at I = 5 A for 100 ns long current pulses. At the same time, longer pulses (∼300 ns) produce a more uniform spectrum between 6 and 8 μm with a FWHM of around Δλ = 1.8 μm at I = 2 A and Δλ = 1.4 μm at I = 5 A, probably due to heating of the sample during the pulse.

In conclusion, we have demonstrated ultrabroadband superluminescent light-emitting diodes based on QCL designs. The emission spectrum spreads between 6 and 8 μm and is inhomogeneously broadened due to 11 different quantum cascade active regions involved in light generation. A superluminescence peak power of few tens of μW is measured, which is significantly larger than the spontaneous emission power from QCLs of ~1 μW. Further improvement in optical peak power and higher temperature operation can be achieved by using longer ridges and structures incorporating active regions with higher gain. More sophisticated device design with antireflection facet coating and tilted or buried ridges will be necessary in this case in order to reduce the optical feedback and prevent lasing.

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10The basis of this assumption will be discussed later in the letter. Higher waveguide loss will give higher value for mirror loss and smaller effective reflection coefficient correspondingly.
11Using a wet etched facet is technologically simpler and more efficient approach compared to antireflection coating (ARC). The lowest reflection coefficient achieved for 6–8 μm spectral range using multilayer ARC is ~0.1%, which is 1 order of magnitude higher than for the facet etched.
12For comparison, the spontaneous emission power for QCL is typically less than 1 nW.
14ARC on the cleaved facet may be necessary in order to keep the threshold current high enough.
15However, by optimizing the device design in order to increase the gain coefficient, room temperature operation of superluminescent QCLEDs can be achieved in the future.