Keynote Paper

High power quantum cascade lasers for infrared countermeasures, targeting and illumination, beacons and standoff detection of explosives and CWAs

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Conceived in ~1971 [1,2] and first experimentally demonstrated in 1994 [3], quantum cascade lasers have become the most importance sources of infrared laser radiation in the 3.5 µm to >12 µm spectral region. With needs already identified at even longer wavelengths, QCLs are being pursued vigorously as sources of terahertz laser radiation. The mid wave infrared (MWIR) and the long wave infrared (LWIR) regions are, however, significantly more important because of a number defense, homeland security and commercial applications critically require the capabilities of QCLs. These capabilities include size, weight and power considerations (SWaP), which make QCLs unique among all other potential sources of laser radiation in this region including optical parametric oscillators, optically pumped semiconductors and optically pumped solids. In this presentation, I will summarize some of the key advances and status of QCL technology as well as defense and civilian applications of the MWIR and LWIR quantum cascade lasers.

Progress in QCL Performance:

Even though the first QCL operation was demonstrated in 1994, 2002 marks the important point in the QCL development because of the report of the first continuous wave room temperature operation of QCLs at ~9.1 µm [4], using a two-phonon resonance de-excitation scheme for emptying the lower laser level. CW operation of QCLs operating at ~4.8 µm was subsequently reported by Evans, et al. [5]. The progress beyond 2004 was significantly aided by two DARPA programs: (a) L-PAS (laser photoacoustic spectroscopy) for the development of a portable chemical warfare agent (CWA) and explosives sensor and (b) EMIL (efficient mid wave infrared laser) program for the development of high power, high wall plug efficiency QCLs for infrared countermeasures. The former resulted in transforming the QCLs from being a laboratory curiosity to a useful device, through innovations that included the first epi-down mounting of QCLs on coefficient of thermal expansion (CTE) matched AlN submounts using Au:Sn hard solder [6]. The second program was instrumental in raising the CW output power levels of QCLs from a few tens of mW to more than one watt. A crucial advance that resulted from the second DARPA program was a revolutionary new QCL structure design that marked a departure from all the earlier designs that relied on longitudinal phonon resonances for depopulating the lower laser level, e.g., one phonon resonance in case of the first demonstration of a QCL operation [1] and two phonon resonance for the first CW operation of the QCL [4]. The new design, called the non-resonance extraction

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(NRE), removes many, if not all of the severe design constraints imposed by the LO-phonon resonance designs [7]. The NRE design has made it possible to extend the high power, high wall plug efficiency operation of QCLs both to shorter [8] and longer wavelengths [9].

FABRY-PEROT CONFIGURATION QCLS:

Current capabilities of QCLs in terms of power output and wall plug efficiency depend crucially on the wavelength of operation. At the shorter end of the spectrum, shorter than about 3.6 µm, QCL performance is limited by the depth of the quantum wells possible in the presently successful structures that use GaInAs/InAlAs combination of materials. At the longer wavelength end of the spectrum, longer than about 10 µm, the performance of the QCLs is limited by electron free carrier absorption. Table I shows a sample of current best performance of continuous wave operation Fabry-Perot configuration (broad band output around the central design wavelength of the QCL). Generally high power QCLs, when operated CW, require thermoelectric cooling to maintain the QCL active region temperature at a point where good performance can be obtained. Furthermore, since the emitting region is typically 2-3 µm high and 8-10µm wide. Thus the laser output from the end facet emerges in a fan that is ~90° X 60° wide. To be able to utilize all of the power generated by the QCL, it is necessary to collimate the beam by placing appropriate optical elements close to the exit face. The performance data have been obtained from QCLs that fully packaged in hermetically sealed butterfly packages and have beam collimating optics as well as the TEC within. The back facet has a high reflectivity coating a while the front facet has a partially reflective coating whose reflectivity is optimized for extracting the maximum amount of power from the device. The output emerges as a collimated beam rather than a widely diverging beam that would be obtained from the end facet of the QCLs. By convention, the wall plug efficiency given in Table I, does not take into account the power consumption by the TEC. Because of the high nascent wall plug efficiency of the QCL, even when we take into account the power consumption by the TEC, overall system efficiency of near 10% is obtained at ~4.6µm.

Table 1. Best continuous wave operation performance of QCLs at room temperature (fully packaged lasers in hermetically sealed butterfly packages containing the QCL, thermoelectric cooler and beam collimating optics).

Best CW/RT Performance of Commercially Available QCLs (w/TEC)		
Wavelength	Power Output (W)	WPE
~4.6 µm	> 4.0 W	> 16%
~4.0 µm	> 2.5 W	~ 10%
~7.1 µm	> 1.4 W	~ 10 %
~9.3 µm	> 2.0W	~ 12 %

Thermal management at the QCL chip level is important because the superlattice forming the QCL has relatively low thermal conductivity normal to the layers, which makes it advantageous to operate the QCLs in a high duty cycle pulsed mode. This entails operating QCLs with 100ns-500ns pulses with a duty cycle as high as 50%. The "off-time" between pulses is sufficiently long to remove the heat from the active layers before the next pulse comes along. High duty cycle operation assures high average powers for the QCLs. As a rule, QCW operation QCLs provides average powers that are comparable to the CW powers available from the same QCL material. However, QCW operation does not require utilization of a thermoelectric cooler, resulting in a much simpler and much smaller QCLs system for the same power output. For many practical applications, QCW operation with high duty cycle is sufficient and true CW operation is not needed because the relatively slow response of the detection schemes used for many applications. Figure 1 shows a miniaturized high average power QCW QCL package, which includes the QCL in the hermetically sealed butterfly package with beam collimating optics, but no TEC and the necessary pulse drive electronics. The entire package weight 50 g (<2 oz), making it ideal for many applications where size and weight are critically important.

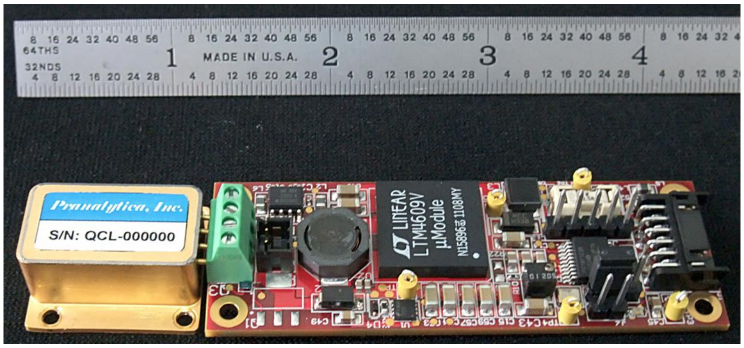

Figure 1. QCW operation QCL in a miniature package along with pulse driver electronics (package dimensions: 1" W x 4.25" L x 0.5" H; weight: 50 g)

Table 2. Best quasi-continuous wave operation performance of QCLs at room temperature (fully packaged lasers in hermetically sealed butterfly packages containing the QCL and beam collimating optics).

Best QCW/RT Performance of Commercially Available QCLs (noTEC)		
Wavelength	Power Output (W)	System Efficiency
~4.6 µm	> 3.5 W	> 12%
~4.0 µm	> 2.0 W	~ 7 %
~7.1 µm	> 1.5 W	~ 12 %
~9.3 µm	> 2.0 W	~ 12 %

Table 2 provides average power output and wall plug efficiency data for QCW operation of QCLs at room temperature. The stated wall plug efficiency is the true efficiency of the QCL system, including the losses in the pulse generation circuit, i.e., it is the efficiency that a system integrator can utilize.

There are other laser sources that cover the spectral region form about 3.5 μm to 12 μm. However, QCL stands out as a unique source of laser radiation in this spectral region as seen from the comparison with some of the other contenders (Table 3).

Table 3. A comparison between available laser sources in the 3.5 μm to 12 μm spectral region.

Source	Type	Wavelength	CW/RT Power	WPE
Optical parametric oscillators (OPOs)	Solid/optically pumped by another laser	400 nm – 10 μm	Usually pulsed	Low
Optically pumped semiconductors (OPSLs)	Solid/optically pumped by another laser (may require cryogenic cooling)	< 5 μm	~ 1 W	Low
Optically pumped doped ZnS	Solid/optically pumped by another laser	2 μm to ~ 5 μm	Up to 3 W	Low
CO_2 lasers	Gas	Discreet wavelengths from 9 μm to 11 μm	kWs	~10 %
QCLs	Solid/direct electrically pumped	~3.8 μm to > 12 μm	> 4 W	~15-20%

Compared to all other sources, for powers less than ~10 W, QCLs are ideal because they are solid state devices, convert electrical energy directly into optical energy, are small and efficient. CO_2 lasers have comparable wall plug efficiency and produce very high powers, but they have a limited wavelength reach, are discretely tuned and are gas lasers, which makes them unsuitable for applications where ruggedness and resilience to vibration and shock are required. Thus, where SWaP issues are paramount, QCLs appear to be ideal choices.

Applications of Fabry-Perot Configuration QCLs:

As expected, the Fabry-Perot configuration provides no wavelength selection within the laser cavity and the QCL output is broad band covering a substantial fraction of the gain spectrum of the device. Typically, the output is ~250 nm wide in the MWIR and LWIR regions. In the era of asymmetric warfare and ever increasing dangers of urban terrorism, several critical needs have been identified where such output is quite useful for a number of defense and security applications including directional infrared countermeasures, target illuminators, pointers and designators, and friend-or-foe beacons.

Infrared Countermeasures: With proliferation of illegally obtained shoulder fired missile (MANPADS), terrorists and non-state actors have acquired a capability of attacking airplanes and helicopters. The traditional technologies that use chaff and flares provide only limited defense against MANPADS. For over a decade, it has been recognized that laser based infrared countermeasures can be significantly more successful in thwarting the dangers posed by MANPADS. Two of the critical spectral regions important for laser based infrared countermeasures are covered by high power MWIR QCLs. Current generation of directional infrared countermeasures use a variety of optically pumped lasers including fiber lasers, optically pumped semiconductor or other solid state lasers and optical parametric oscillators (see Table 3). However, with the development of QCLs and their commercial availability, QCLs have already begun to displace other lasers in DIRCM applications.

Testing Infrared Countermeasures: Evaluating the effectiveness of infrared countermeasures is an important activity and MWIR QCLs are seen as ideal for replicating the infrared signatures of the engine exhaust from aircraft.

Target Illuminators, Designators and Pointers: A very important battlefield applications of lasers is in the area of providing illumination and target designation including pointing. Warfighters rely on the availability of laser based target pointers. Near infrared lasers have been widely used for these applications for many years and have been successful. However, with the ubiquitous availability of night vision goggles and cameras, the adversary has the capability of detection when the near IR target illuminators are being used. The ultra small and ultra lightweight packaging of QCLs (Figure 1) now makes it possible to adapt the MWIR/LWIR QCLs for target illuminators.

Friend-or-Foe Beacons: Another very important battlefield need is the FoF beacons. Such beacons have traditionally use either visible or near IR lasers with considerable success. Use of longer wavelength radiation laser sources has two advantages. The first is the same as we identified above for target illuminators. The second one and equally important is the very low atmospheric scattering of the longer wavelength radiation by smoke, dust, fog, smog and other particulate matter, because of the λ^{-4} dependence of light scattering.

TUNABLE LASER CONFIGURATION QCLs:

Laser sources that have broad gain spectra and provide a broad bandwidth radiation when operated in Fabry-Perot configuration but can be made to operate on a single tunable wavelength by inclusion of a wavelength dispersive element within the optical cavity. Even though Fabry-Perot configuration with wide band width output radiation has many important applications as seen above, there is a need for tunable narrow bandwidth radiation in the MWIR/LWIR spectral region, which heretofore could only be covered by optical parametric oscillators or cryogenically cooled lead salt diode lasers. With the advent of broad gain bandwidth QCLs that operate at CW at room temperature, tunable QCLs have become important sources of radiation wherever the application depends on the spectral characteristics of the radiation. These applications include spectroscopic studies of materials, such as laboratory investigation of materials, in-situ detection of pollution and presence of toxic substances including chemical warfare agents (CWAs) and explosives and standoff detection of CWAs and explosives (IEDs).

The most commonly used geometry of a tunable QCL consists of laser gain medium enclosed in an optical cavity that includes a dispersive moving grating. By changing the angle of the grating, the resonant wavelength of the laser cavity can be controlled (Figure 2). This scheme has been widely deployed and has been quite successful. It is, however, susceptible to mechanical shock and vibration, which limits its employment in field applications. Another significant limitation for tunable QCLs with a moving grating is a slow tuning speed on the order of 10s of milliseconds. In real environment, where large urban or rural areas need to be scanned, tuning rate on the order of microseconds is required.

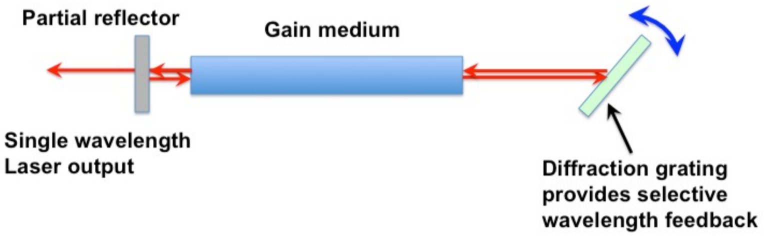

Figure 2. Traditional EC QCL with angle tuned grating

Rapid Tuning of EC QCLs (Switching Time <700 ns)

A novel external cavity QCL configuration that does not suffer from these two limitations has recently been developed [10]. In these devices the ultra-rapid wavelength tuning is achieved using an electrically controlled acousto-optic modulator. A radio-frequency acoustic wave in AO modulators is generated in a transparent material (germanium in case of LWIR region) and this acoustic wave forms an index grating. The incident light waves from the laser are deflected by this grating (Figure 3). The angle of the deflection is controlled by the choices of optical and acoustic wavelengths. The direction of the lasing is determined by the laser resonator cavity so the output laser wavelength can be electronically selected by changing the acoustic frequency of the AO modulator, thus changing the Bragg angle condition for the selected wavelength. The response time of the modulators and, as a consequence, of the entire laser system is determined by the transit time of the acoustic wave across the material and typically lies in the MHz range.

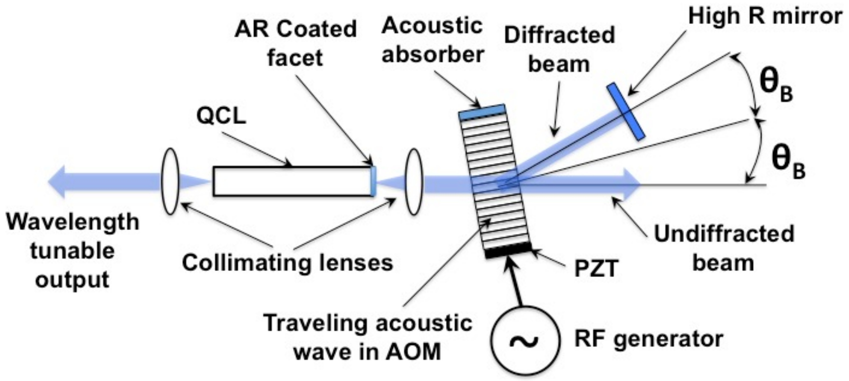

Figure 3. Schematic of acousto-optic modulator tuned quantum cascade laser

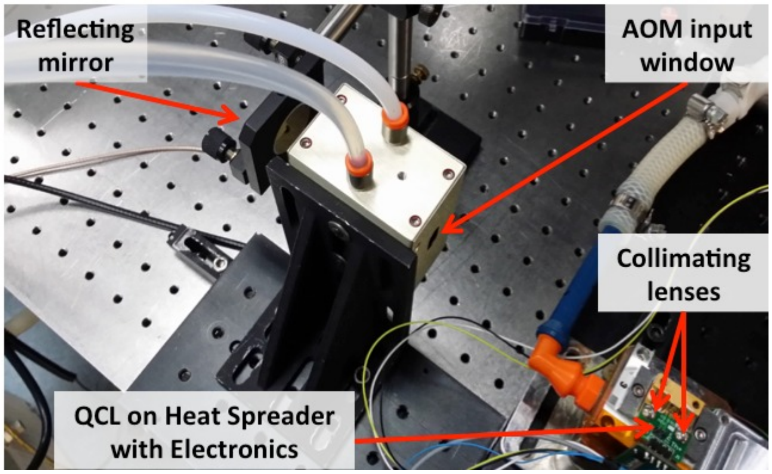

Figure 4. Benchtop realization of AOM tuned EC QCL.

Figure 4 shows a benchtop version of a AOM tuned EC QCL. The measured switching time for changing the AOM controlled EC QCL lasing wavelength was less than 700 ns for switching between any wavelengths within the lasing region of the QCL. To demonstrate the ultra rapid spectral measurement capability for the AOM-controlled EC QCLs, we measured the absorption spectrum of Freon

(R134a, cell length 5 cm, room temperature, concentration of 2.63%) that has a broad infrared spectral signature in the 9 μm region. The measurement was carried out in a single wavelength sweep when acousto-optic frequency was linearly changed from 42 MHz to 48 MHz in 17μs. Figure 5 shows the transmission signal collected using a room temperature MCT detector with and without the Freon cell present in the optical path (red and blue curves, respectively). The change in the AOM frequency resulted in lasing wavelength sweep across the QCL tunable range.

Figure 6 shows corresponding absorption spectrum (processed data from Figure 5) and Freon absorption spectrum simulated using PNNL Spectral Database convolved using the measured linewidth of laser emission. A good correspondence was observed between the experimental and simulation data. The fact that the experimental data were collected in 17μs without statistical averaging clearly demonstrates the advantage of rapid tuning for AOM controlled EC QCLs.

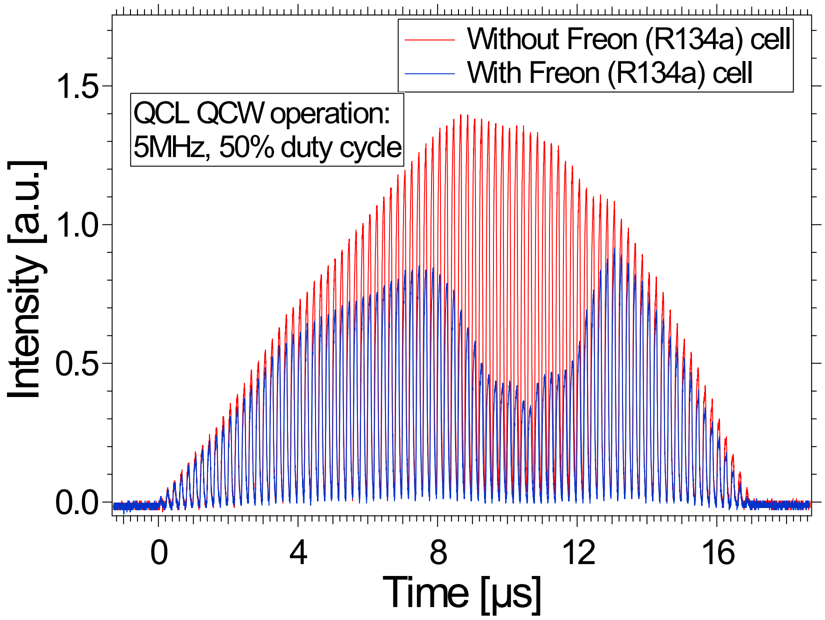

Figure 5. Experimental transmission data with and without the Freon (R134a) cell present in the optical path. AOM frequency was linearly changed from 42MHz to 49MHz, which resulted in wavelength tuning. QCL was driven in QCW mode with 5MHz repetition rate and 50% duty cycle.

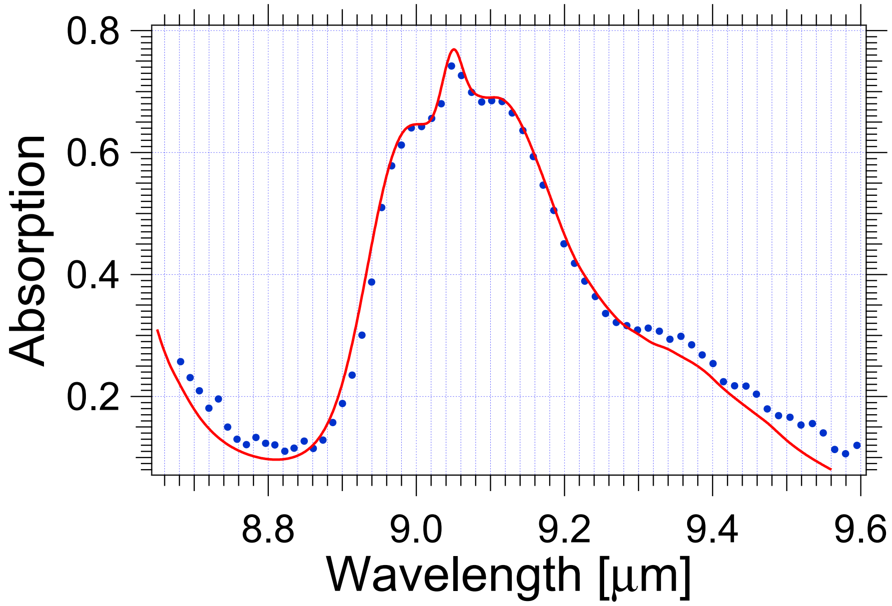

Figure 6. Processed experimental Figure 4 data (blue points) vs PNNL data for Freon (R134a). PNNL data were convolved with the measured linewidth of the laser emission (red line). The Freon spectrum was calculated using 2.36% concentration, temperature of 23°C, and pressure of 760 Torr.

Figure 7 shows a compact packaged version of the benchtop AOM tuned EC QCL set up for measuring transmission spectra of gases.

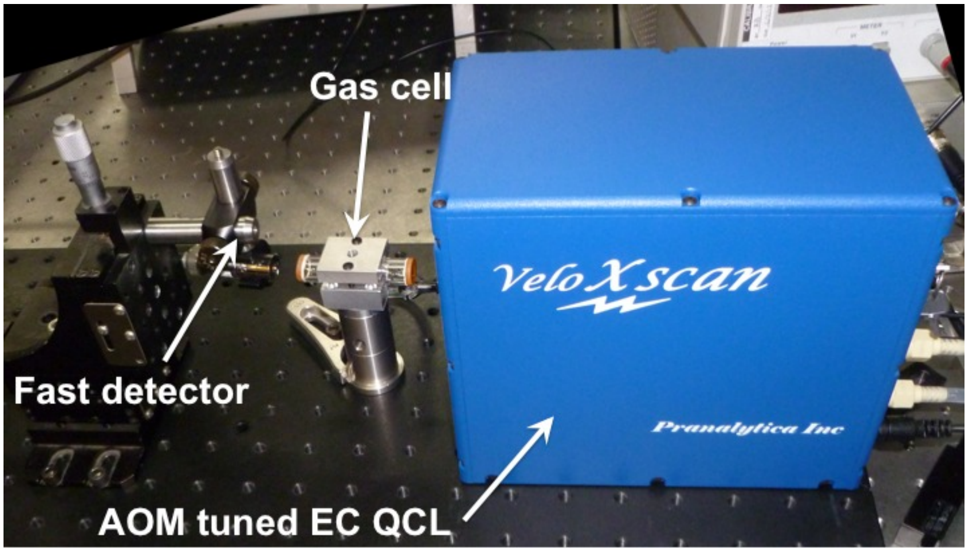

Figure 7. Gas transmission measurement setup using fully packaged AOM tuned EC QCL (VeloXscan).

The above experimental data clearly demonstrate that AOM tuned EC QCL offers unique advantages of very fast tuning capability with spectral scan measurement time of under 20μs and wavelength switching time of < 700 ns for switching wavelengths between any two points within the spectral scan width of the QCL. The AOM tuned EC QCL has no moving parts and therefore it is inherently amenable to be ruggedized for demanding field applications, including mounting on moving or flying platforms. The flexibility offered by the AOM approach will significantly improve the capabilities of external cavity QCLs. The AOM tuned QCLs (VeloXscan) will find immediate use in applications where the ultra-rapid scanning rate is of utmost importance, including standoff detection of IEDs and CWAs, combustion and explosion dynamics, optical frequency domain reflectometry (OFDR) as well as measurements of dynamic spectral changes during chemical and biological reactions.

CONCLUSION

In above brief review we have shown the vitality of the field of quantum cascade lasers that are operated in Fabry-Perot configuration (broad band output) as well as when they are configured in an external cavity geometry, where one of the mirrors forming the laser cavity is a wavelength dispersive element. The new developments are being driven by the recognition that for MWIR and LWIR regions, QCLs offer unique advantages over other sources of coherent radiation in the given spectral region.

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