Prospects for quantum cascade lasers as transmitters and local oscillators in coherent terahertz transmitter/receiver systems


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ABSTRACT

Coherent terahertz radar systems, using CO$_2$ laser-pumped molecular lasers have been used during the past decade for radar scale modeling applications, as well as proof-of-principle demonstrations of remote detection of concealed weapons. The presentation will consider the potential for replacement of molecular laser sources by quantum cascade lasers. While the temporal and spatial characteristics of current THz QCLs limit their applicability, rapid progress is being made in resolving these issues. Specifications for satisfying the requirements of coherent short-range THz radars will be reviewed and the feasibility of incorporating existing QCL devices into such systems will be described.

Keywords: THz quantum cascade laser, THz imaging, radar cross-section, transmitter, receiver, mixer, coherent detection.

1. INTRODUCTION

The ERADS Program, sponsored by the U.S. Army National Ground Intelligence Center (NGIC) has led to the successful operation of coherent transceivers operating at frequencies from 160 GHz to 1.56 THz. These source/receiver systems are used in indoor compact radar range configurations, along with physical scale models, to provide microwave and millimeter radar signature data on targets of interest.1-5 At lower frequencies (160 GHz to approximately 1.0 THz) harmonics of amplified and multiplied microwave signals have been used, and at higher frequencies (above 1.0 THz) CO$_2$ optically pumped molecular gas lasers (OPL), have been employed as transmitter and local oscillator (LO) sources. The transmitter and LO signals are mixed together in high-frequency, room-temperature Schottky diodes for phase and amplitude processing of the intermediate frequency (IF) signal. The extraordinary sensitivity of narrowband coherent detection has also enabled the demonstration of two and three-dimensional THz imaging of weapons concealed under clothing.6-8

While the coherent transceivers described in Ref. 1-5 have met the system requirements for radar scale model measurements, they are complex in design, expensive, and in the case of OPLs, occupy a large footprint for an indoor range. This is particularly true when the transceivers are built with sufficient bandwidth to provide results equivalent to synthetic aperture radar (SAR) field data, a requirement of current ERADS systems.

The recent extension of quantum cascade laser (QCL) operation to THz frequencies9 provides a new radiation source for both transmitter and LO use, with the potential for greatly reduced complexity, cost, and size, which would open up a wide range of applications for coherent THz systems. Current state-of-the-art THz QCL (TQCL) performance, however, is deficient in many respects for coherent transceiver applications. In this paper their present strengths and deficiencies will be discussed and the effort at the University of Massachusetts Lowell's Submillimeter Wave Technology Laboratory (STL ) to deal with some of the key issues relevant to ERADS radar range design will be described.

It is important to point out that because of the very limited availability of TQCLs it is necessary to have TQCL design, growth and fabrication capability, as well as THz circuit and system designers, in order to realize the potential of

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these novel sources. In this regard, the contributions of the UMass Lowell Photonics Center in successfully growing material and fabricating lasers is particularly noteworthy.

2. TRANSMITTER and LO REQUIREMENTS for COHERENT THz RADAR SYSTEMS

The configuration envisioned for a coherent THz transceiver using QCLs is shown schematically in Figure 1.

QCL 1 is employed as the LO. Its beam, propagating in free space, is split and illuminates the reference mixer, M1, and also drives the receive mixer, M2. The room temperature mixers are high-frequency Schottky diodes housed either in a quasi-optical antenna structure or in a fundamental mode waveguide. QCL 2, the transmitter, is also split and a portion illuminates mixer M1 while the rest is beam expanded, collimated and directed towards the target. Scattered radiation from the target is collected by the same collimator and the backscattered radiation is directed to the receive mixer M2. The intermediate frequency (IF), \( (\nu_{\text{transmitter}} - \nu_{\text{LO}}) \), of both the reference and receive mixers, ideally in the 1-10 GHz range, can be amplified, further down converted and processed coherently with high frequency electronic instrumentation thus preserving the amplitude and phase of the signal scattered from the target. This near-monostatic configuration and coherent processing of THz signals has been the standard design of ERADS radar ranges (see, e.g., Reference 5, Figure 1).

The source requirements for achieving acceptable performance of such a system can be summarized as follows:

1. Continuous wave (CW) operation.
2. Emission in the THz atmospheric windows.
3. A high degree of spatial coherence.
4. Sufficient power to be used as a LO for Schottky diode mixers.
5. Long-term frequency stability of better than ±50 kHz.
6. Sufficient power from the transmitter to obtain good signal-to-noise ratio (S/N) of radiation scattered from the target.
7. Sufficient tunability of the transmitter frequency to achieve the required range resolution.

Current and projected capabilities of TQCLs will be discussed within the context of items 1-7.
2.1 Continuous Wave Operation

CW operation is not an issue for most TQCLs, as long as the devices can be maintained at a sufficiently low temperature under dc bias conditions. Bottlenecks in the lower laser level which prevent CW operation in certain laser systems are automatically engineered out as an integral part of the design of the QCL level structure. At the present stage of TQCL technology, CW operation is much preferred over pulsed operation for coherent transceiver applications. In the pulsed mode the frequency will change by several hundred MHz as the voltage first sweeps above oscillation threshold, and again as it turns off. This level of "frequency jitter" would have to be gated out (see Section 2.5). In addition, peak pulsed power and CW power are quite comparable for TQCLs. Since pulsed operation necessarily requires a larger receiver bandwidth, the system S/N will be reduced. Unfortunately, the required dc bias power of several watts quickly consumes cryogenic liquids, especially low-heat-capacity liquid helium which boils off at the rate of one liter/hour/watt, so CW operation for extended periods of time is problematic.

2.2 THz Atmospheric Windows

THz atmospheric transmittance (0.3 - 3.9 THz) measurements were made over a 1.7 m path using a Fourier transform spectrometer (FTIR) at a resolution of 4.5 GHz. The data were acquired at P = 760 mm Hg and T = 27°C for 5 different values of relative humidity (RH) between 6% - 52%. The complete data array is available online at stl.uml.edu. Figure 2 is a plot of the THz transmittance for the lowest and highest values of RH. Taking into account the operational range of current TQCLs, five regions of acceptable transmittance are considered, centered at 1.51, 1.98, 2.1, 2.53, and 3.43 THz.

![Graph of THz transmittance](image)

Fig. 2. Measured atmospheric THz transmission for 1.7 m path length at 6% (red) and 52% (blue) relative humidity.

Figure 3 plots the atmospheric attenuation (dB/m) in the five "windows" versus relative humidity. Even short-range (30-50 m path lengths) applications in standard air-conditioned environments will suffer significant atmospheric attenuation, particularly at the higher window frequencies, 2.1 THz and above. For example, the loss for a 30 m path at 50% relative humidity is 27 dB at 2.5 THz. The attenuation of clothing and packaging materials also increases rapidly with increasing THz frequency. Consequently, the lower frequency THz windows are much preferred.
Unfortunately, present QCL performance falls off rapidly with decreasing THz frequency below 2.0 THz\textsuperscript{13}, and only recently has QCL operation been reported in the 1.2 - 1.6 THz region\textsuperscript{12}, with peak power at the several hundred microwatt level near 4.2K. Based on the early stage of development and the considerable ongoing scientific activity, improved QCL structure and laser cavity designs, as well as alternative materials and better growth techniques should lead to improved output power. Ideally, QCLs would be able to operate at the 5-10 mW CW power level, above liquid nitrogen temperature, for frequencies in the 1.5 - 2.5 THz range. However, it's not clear that the controlling physical parameters of these devices, such as electron intersubband scattering rates, free carrier absorption losses, etc., will permit such performance levels to be achieved. Examples of state-of-the-art QCL sources operating at or below 2 THz\textsuperscript{12-14} are presented in Table 1, and illustrate the present-day challenges.

### Table 1. CW performance levels of TQCLs below 2.0 THz.

<table>
<thead>
<tr>
<th>THz frequency</th>
<th>Maximum temperature</th>
<th>Maximum measured power (mW)</th>
<th>Power at 77 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 \textsuperscript{(13)}</td>
<td>47 K</td>
<td>17</td>
<td>----</td>
</tr>
<tr>
<td>1.9 \textsuperscript{(14)}</td>
<td>87 K</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>1.34 – 1.58 \textsuperscript{(12)}</td>
<td>58 K</td>
<td>0.3</td>
<td>----</td>
</tr>
</tbody>
</table>

#### 2.3 Spatial Coherence of TQCLs

Coherent transceivers require radiation signals with a high degree of spatial coherence. THz heterodyne detection requires coupling of overlapping single spatial modes of the LO and transmitter, either in a fundamental mode waveguide or by combining the overlapping beams onto a quasi-optical antenna structure. In either case optimum receiver performance is achieved when a free-space Gaussian beam is matched to the antenna pattern of the receiver with a combination of horns, lenses, and reflectors. Since the active region is only about 10 microns thick, TQCL beams emerging from the standard Fabry-Perot (FP), semiconductor cavity design suffer from diffraction and scattering effects due to the small (relative to the wavelength) cavity dimensions, as well as the presence of higher order transverse modes. This leads to multi-lobed, highly diverging output beams. In contrast to OPLs, the gain bandwidth is large, leading to oscillation in multiple longitudinal modes. However, stable single longitudinal mode output can usually be achieved by operating at bias voltages slightly above threshold. Two waveguide designs employed with FP cavities are the semi-insulating, surface plasmon (SI-SP) and metal-metal (MM) structures.\textsuperscript{15} The SI-SP design is easier to fabricate, has less beam divergence and is generally free of higher order transverse modes, thus allowing single-frequency operation. MM structures provide greatly improved mode confinement. This is apparently critical to long-wavelength operation, as all reported QCLs operating at or below 2.0 THz use the MM structure, which also has superior temperature performance compared to the SI-SP waveguide. MM laser beams are highly divergent and generally contain multiple frequencies (transverse modes). Methods for reducing this beam spread\textsuperscript{16,17} and suppressing transverse modes\textsuperscript{18} have recently been reported. At the present time however, the beam pattern of TQCLs is far from ideal, whichever FP waveguide structure
is employed.

2.4 TQCLs as LOs for Schottky Diode Mixers

An indication of the poor beam quality is the present inability of QCLs to drive a Schottky diode mixer and achieve a good receiver noise temperature, in spite of measured QCL powers in excess of typical requirements for THz LOs. At STL we have employed a hollow dielectric waveguide (1.8 mm ID, 43 mm long) placed adjacent to the facet of a 2.9 TQCL to produce an approximately Gaussian beam pattern with a low far-field beam divergence, determined by the dielectric waveguide's inner diameter. This was accomplished at the cost of attenuating the measured laser intensity by nearly 5dB. Using a similar approach with a 2.4 TQCL a video responsivity of 15V/W was measured for a corner-cube-mounted, whisker-contacted, Schottky diode. The detector is designed to receive a 1.8t. Gaussian beam waist, w0, matched to the antenna pattern of the whisker's traveling wave, hence it requires an incident beam with a high degree of spatial coherence. The measured responsivity is a factor of six less than earlier measurements at 2.5 THz, using OPL sources, which indicates that the coherence of the QCL beam remains suspect, even after the dielectric waveguide's obvious spatial filtering effect. Despite their poor beam quality QCLs have been successfully used as LOs for superconducting hot electron bolometer (HEB) mixers and produced a record low receiver noise temperature of 1050K, for frequencies above 2.5 THz. Superconducting HEBs mixers work well with QCLs because they require 30-40 dB less LO power than Schottky diode mixers, hundreds of nanowatts versus several milliwatts. However, Schottky diodes are much preferred to HEBs for most applications because of their larger bandwidth and room temperature operation. From the HEB mixer results estimates were that only about 4% of the QCL power could be effectively coupled into the antenna pattern of the HEB mixer. Thus, barring any improvements in TQCL beam quality, CW power in excess of 50 mW may be required for Schottky mixers, a level of output power close to the highest achieved to date.

Recently, vertical-direction TQCL output via a surface-emitting, second-order distributed feedback grating and a surface photonic crystal pattern have been demonstrated, with improved mode quality (in one dimension) and increased single mode tunability. While adding complexity to the fabrication process, emission from a much larger surface area and increased mode control could overcome some of the problems discussed here. However, at this time it's unclear which cavity design, whether already demonstrated or still to be developed, is optimum for coherent system applications.

2.5 TQCL Frequency Stability Requirements for Coherent Imaging

Imaging radar systems depend on phase and amplitude stability of the signal returned from a target, which is combined with a LO in a sensitive mixer and downconverted to an IF with preservation of phase and amplitude. At microwaves, frequency control and shift techniques have been developed which lock transmitter and LO together, even as they are tuned to provide range resolution. ERADS coherent THz radar systems rely on the inherent frequency stability of a pair of independent OPLs which are not locked together. However, the IF phase of the output pair is measured and provides a tracking reference for the IF signal from the receive mixer. A shift in phase of the signal returned from the target due to an uncontrolled shift in frequency introduces noise and reduces the resolution of the processed image. For near noise-free imagery the phase shift should not exceed several degrees. The phase shift, \( \Delta \phi \), (in degrees) due to a frequency shift, \( \Delta v \), is given by; \( \Delta \phi = (360) \frac{\Delta \nu}{c} \), where D is the round-trip distance to the target and c is the speed of light. For ERADS compact radar ranges D = 25 m. If we require \( \Delta \phi \leq 3^\circ \), then \( \Delta \nu \leq 10^8 \text{ Hz} \). Thus, sources with a frequency jitter of \( \pm 50 \text{ kHz} \) or less are required for coherent image processing.

Well designed OPL systems can easily meet this requirement using ultrastable CO2 pump lasers and THz laser cavities in a low-vibration environment. To illustrate the required stability, a 2.0 m long laser cavity operating at 1.5 THz cannot change by more than 0.07 microns in length during the time required to form an image, typically tens of minutes.

Stabilizing the frequency of TQCLs to nearly 1 part in \( 10^8 \) is much more challenging since the stability of the optical cavity in this case is limited by fluctuations in n, the index of refraction of the active medium. Changes in temperature due to power supply noise generate frequency shifts via the dependence of n on temperature. Fluctuations in the ambient temperature will, of course, also cause \( \nu \) to shift. Barberi, et.al., measured \( \frac{d \nu}{d \nu} = 6 \cdot 10^9 \text{ Hz} / A \), and \( \frac{d \nu}{dT} = 10^8 \text{ Hz} / K \), for a 3.3 TQCL of the bound-to-continuum (BTC) design. We have measured \( \frac{d \nu}{dT} = 6.5 \cdot 10^9 \text{ Hz} / A \) for a 2.4 TQCL with a similar structure, in good agreement with Barberi's result. Betz, et.al., determined a somewhat greater frequency shift, with \( \frac{d \nu}{dT} = 45 \cdot 10^9 \text{ Hz} / A \) for a 3.0 THz laser of the resonant phonon (RP) design. Since QCLs require several watts of drive power, I \( \sim 0.1-1 \) amp, \( V \sim 2-10 \) volts, highly stable dc power
supplies with RMS noise levels of less than 10 microamps are needed to achieve the required frequency stability. Some commercial laser diode drivers can satisfy this low-noise specification but typically fail to meet the current or voltage requirement for QCLs. Consequently, reports to date on stabilizing TQCL linewidths below the 1 MHz level have used battery-driven bias circuits and a feedback loop to lock the QCL circuit to a second, more frequency-stable source. Betz, et al., reported a narrowing of a 1.2 GHz IF product generated by a QCL, a 3.1059368 THz OPL and a 24.6 GHz microwave signal, all directed into a corner-cube-mounted Schottky diode mixer. Using a source-locking frequency counter, which generates an error signal to the QCL bias circuit, they observed a 65 kHz wide (-3dB) IF signal with the feedback loop closed, in contrast to a 350 kHz wide IF signal with the QCL free running. This important result demonstrated frequency stabilization of a TQCL for the first time, however the locked signal was considerably wider than the OPL reference line. For future development of a more practical reference source, such as an upconverted microwave signal, it is important to uncover the sources of noise that limited the QCL from narrowing to the OPL linewidth.

The source-locking frequency counter is a microprocessor-based instrument with a sequence of pre-programmed operations designed to phase lock an external frequency to an internal, stable and settable source. The "black box" nature of its operation limits remediation efforts in cases where phase locking fails. At STL, a more controllable, analog, frequency locking approach was adopted to better understand the issues. The experimental set-up is shown in Figure 4. A 2.409293 THz OPL line, obtained by pumping CH$_2$DOH was mixed with a QCL laser operating approximately 1 GHz below the OPL, in a corner-cube-mounted Schottky diode mixer. The GHz IF signal was amplified (56 dB) and downconverted to 18 MHz with a microwave mixer and synthesizer source. The 18 MHz signal was amplified (20 dB) and passed through a 400 kHz (-3 dB) wide RF bandpass filter (BP) centered at 18 MHz. The synthesizer signal was modulated at 62 kHz with a modulation depth of 500 kHz, and the 62 kHz modulation frequency was used as a reference signal for a lock-in amplifier, whose input was the RF-rectified 18 MHz signal. The lock-in output at the reference frequency is the first derivative of the bandpass signal which, fed back to the QCL bias circuit at the proper gain setting and lock-in time constant, will hopefully lock the frequency, \( v = (v_{\text{OPL}} - v_{\text{QCL}}) \) to the synthesizer signal. In principle, \( v \) can be more stable than the reference frequency, \( v_{\text{OPL}} \), if the feedback loop is sufficiently agile to adjust \( v_{\text{QCL}} \) to correct for the jitter of \( v_{\text{OPL}} \), while simultaneously correcting for current fluctuations in the battery-driven QCL bias circuit. Figures 5a, 5b, and 5c, show the unlocked and locked spectra of \( (v_{\text{OPL}} - v_{\text{QCL}}) \), taken over a frequency sweep duration of approximately 60 seconds, indicating a narrowing, from several hundred kHz to 7 kHz (-3 dB) for the optimum parameters of the feedback circuit. The measured linewidth, \( \Delta v \), is narrower than the OPL reference, \( \Delta v_{\text{OPL}} \), by a factor of 4, showing that the lock circuit is at least partially tracking the OPL frequency jitter. Further details of this experiment are described elsewhere. The results demonstrate, for the first time, frequency stabilization of a single mode TQCL to that of an external source. Further, the temporal coherence of the locked QCL is more than adequate for ERADS radar range applications. The next critical step will be to identify a practical source for locking, to replace the OPL.

![Circuit configuration used in locking \( v_{\text{QCL}} \) to \( v_{\text{OPL}} \). The modulated microwave source and BP filter provide an error signal that stabilizes the IF frequency, \( (v_{\text{QCL}}-v_{\text{OPL}}) \), and locks the quantum cascade laser to the OPL reference source.](image)

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2.6 TQCL Transmitter Requirements

Experience with ERADS radar systems indicates that a minimum of 120 dB of detection range, defined as the ratio of the transmitter power to the minimum detectable power for a 1 Hz bandwidth, is required to achieve acceptable performance. Assuming that a coherent receiver sensitivity of $10^{-19}$ W/Hz can be achieved (equivalent to a receiver noise temperature of approximately $10^6$ K), at least one microwatt of transmitter power is required to obtain a 10 dB S/N ratio for a 1 Hz data rate. CW operation and coherent integration effectively provide sub to single Hz bandwidths, so S/N estimates based on a 1Hz bandwidth are valid for these systems. Current performance of TQCLs provides sufficient narrowband power for transmitter requirements, even under the assumption that a substantial portion of the beam's power has to be filtered out to achieve the large, planar wavefront that is required for a compact range configuration. However, rapid and precise source tunability sufficient to range-resolve scattering centers on a target is beyond the current state-of-the-art of these devices.

2.7 TQCL Frequency Tuning Requirements

To emulate present day SAR radars, ERADS systems need to achieve at least 1 cm of range resolution. Bandwidth and range resolution are related by the simple equation $B = c/2\Delta R$

where B is the bandwidth required to produce a range resolution $\Delta R$. A 1 cm range resolution thus requires 15 GHz of bandwidth which is not realizable with existing FP, cleaved-cavity TQCLs. While the large gain bandwidths, indicated by the presence of multiple longitudinal modes, is more than sufficient to enable signal processing for high range resolution, the technology to convert this potential to swept, single mode operation has not yet been developed.

At STL we have coupled the sideband generation technique with TQCLs and have produced sufficient bandwidth to meet SAR range resolution requirements. Eighteen GHz of tuning was demonstrated by sweeping the upper sideband through several well-documented $D_2O$ molecular transitions using a 2-20 GHz microwave synthesizer and a

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Fig. 5. (a) and (b). Frequency spectra of ($v_{QCL}$-$v_{UPL}$) under locked conditions. Scan time is 1 min. (c) Similar scan with free-running QCL.
2.407750 CW TQCL. The experimental set-up is shown in Figure 6(a) and the spectra obtained are displayed in Figure 6(b) (from Reference 20).

![Diagram of TQCL set-up and spectra](image)

**Fig. 6.** (a) Setup for sideband generation spectroscopy of D₂O with a 2.408 THz QCL source. (b) Upper sideband spectra of D₂O at 500 mTorr pressure. Lines 1, 3, 7, and 9 are identified as D₂O rotational transitions. (From Ref. 20)

The sideband generation method for producing the requisite bandwidth is currently used in ERADS OPL-based radar systems. As pointed out in Section 2.3, the poor spatial mode quality of TQCLs reduces the efficiency of coupling radiation into single mode mixers, whether they are used as downconverters or sideband generators. The overall efficiency of sideband-to-QCL ratio in Reference 20 was approximately 2 x 10⁻⁴ with the sideband power in the range of several hundred nanowatts. Clearly, improving TQCL mode quality is important here, but better THz Schottky diodes and improved mixer designs may be even more effective in increasing sideband generator efficiency. Recently, Erickson has demonstrated improved sideband generator performance at 1.56 THz with the first THz balanced mixer design. This 4 port waveguide mixer addresses a key limitation of previous THz Schottky diode mixers, by separating the drive and signal ports, thus eliminating the need for external diplexers when the device is used as a downconverter. In addition, the drive power is substantially suppressed at the signal port, eliminating the requirement for filtering out the drive with dichroic elements, such as Si etalons, when the mixer is used as a sideband generator. Using 1 mW of OPL drive power, a maximum sideband generator efficiency of 2.3 x 10⁻² was measured at the signal port, with the drive suppressed approximately 23 dB. Efficiency increased with microwave power up to the maximum used, 1.3 mW, at 10 GHz. To avoid the risk of burning out the diodes no attempt was made to optimize the sideband efficiency, so further improvement is likely. The membrane diodes used in Erickson's balanced mixer design are produced at Cal Tech's Jet Propulsion Laboratory. A fabrication run currently underway will provide an array of 1.5-3.5 THz diodes which will be used in balanced mixers, designed to operate at specified bands over this frequency range. In addition to improving the performance of existing OPL-based coherent transceivers, this project will involve testing of TQCLs as drivers of sideband generators, with the expectation of between one and two orders of magnitude increase in output power as compared to the results from Ref. 20.

**SUMMARY and CONCLUSIONS**

In this paper the state-of-the-art performance of TQCLs has been reviewed in the context of their suitability for use as transmitters and LOs in short range coherent transceivers. The authors have attempted to survey the most recent literature but in such a rapidly evolving technology some relevant contributions may have been overlooked, and we apologize in advance for such omissions.

Based on experience with OPL-based THz transceivers, seven requirements for TQCLs were defined and the current capabilities and limitations of these devices were reviewed. STL has demonstrated techniques for stabilizing and tuning the frequency of QCLs (requirements 5 and 7). Additional development should enable these techniques to perform at the level required for coherent systems. Since requirements 3 and 4 are not strictly independent, solutions here can be anticipated either through increased output power, improved mode quality or a combination of both. Sufficient transmitter power, requirement 6, does not appear to be a problem for TQCL use in ERADS indoor compact ranges, as long as requirement 4 is satisfied. Obviously, the issue is much more serious for longer path lengths and uncontrolled atmospheric conditions.
While requirement 1 is in one sense not a problem, the severe constraint of having to operate a CW device below 77K in order to obtain power at the mW level may be a more fundamental limitation, not amenable to a straightforward engineering solution. The related problem of robust operation at the low frequency end of the THz region may also be more intractable. If these issues can be overcome by novel energy level design, different material choices, improved growth methods, or alternative fabrication techniques then the prospects for wide application of TQCLs will be considerably brighter.

References


