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Letter

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Beam combining of quantum cascade lasers for remote sensing

Abstract: This letter highlights the application of quantum cascade lasers for stand-off detection and remote sensing. In particular, we review the topic of power scaling via beam combining architectures and conclude with remarks on generating axial symmetric irradiance profiles via incoherent aperture beam combining of individual quantum cascade lasers.

Keywords: beam combining; optical sensing; quantum cascade lasers; remote sensing; sensors; stand-off detection.

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1 Introduction

Quantum cascade lasers (QCLs) are electrically pumped unipolar semiconductor lasers. They extend the spectral gamut of the semiconductor laser technology into the infrared and submillimetre (THz) range. QCLs emitting in the mid-infrared atmospheric windows, in particular in the bands between 3.4–5 and 7.5–14 μm, are candidates to establish laser-based stand-off detection and remote sensing next to well-known passive infrared sensing techniques such as thermal imaging, Fourier-transform infrared spectroscopy or radiometry. As the spectral coverage of a QCL is determined primarily by its design features, and not by fundamental material properties, any wavelength in the aforementioned atmospheric windows can be generated with QCLs based on the GaInAs/AlInAs-InP materials system. For this particular materials system, a reliable epitaxial growth and processing technology has been established [1].

Combined with uncooled and cooled infrared detectors and cameras or non-optical detection schemes such as photo-acoustics, QCLs will penetrate industrial sensing and detection as well as security- and defence-related application areas. Examples are the detection of toxic industrial chemicals, multispectral infrared active imaging to obtain chemical information from a distance, infrared illumination and designation, laser radar or free-space optical data links [2–5].

The output power of current single QCL modules is sufficient to serve so-called stand-off detection applications with moderate to low spatial resolution and detection ranges of a few meters. In order to transition from stand-off detection to remote sensing, the output power of the QCL modules has to be increased. There are two ways to achieve this goal: (i) amplification of the output of a single QCL or (ii) combining several QCLs into a common flux tube in order to increase the irradiance on the target to be sensed. Amplification is the way to go if narrow spectral linewidth and tuneability are important features, for example, in chemical sensing [6, 7]. Beam combining is the technique of choice if imaging, illumination or heating is of primary interest as in multi-spectral active imaging, photothermal imaging, probe beam techniques or laser radar [8].

In this letter, we review briefly the properties of QCLs and beam-combining techniques to scale the output power and to shape the spectral and spatial irradiance profiles for imaging and illumination purposes.

2 Quantum cascade lasers

A QCL is a device whose operation is entirely determined by quantum mechanics [9]. The lasing transition occurs between electron subbands in the conduction band formed by a sequence of layers of semiconductor materials with different bandgap energies. The layers are typically a few nanometres thick. The structure can be pictured as an ensemble of coupled quantum wells (QW) embedded between thin barrier layers. At infrared wavelengths, the QWs are based on the ternary compound GaInAs and the barrier layers on AlInAs, respectively. Electron transport, required for electrical pumping, is brought about by quantum mechanical tunnelling of conduction band electrons through the barrier layers. The optical gain is enhanced by cascading several tens of these stacks of alternating QW and barrier layers. The stacks are interconnected by so-called injector regions, which transition the electron's wavefunction of the laser ground state of a QW active region into the upper laser level of the one further downstream. This way, electrons get multiple chances to emit a photon while travelling through the quantum cascade structure when driven by an appropriate applied electrical field.

The lasing wavelength of a QCL is determined primarily by the thickness of the QW active region and not by the band gap energy of the semiconductor material forming the QW layers. This 'freedom from bandgap slavery' [10] is the major difference between QCLs and standard semiconductor interband diode lasers based on electron-hole recombination.

The optical power of a QCL is generated in a waveguide with a rectangular cross section (in the order of 2×10 μm) and a length of 3–5 mm. The waveguide is embedded in a resonator. The following resonator configurations are currently in use:

- Fabry-Perot resonators, formed by two opposing cleavage planes of the semiconductor crystal, which distribute the output power among several wavelengths for illumination purposes;
- distributed feedback resonators, integrated into the semiconductor waveguide structure, which concentrate the optical power into narrow spectral lines;
- external cavity resonators to tune the output power continuously over a large spectral range (more than 30% of the centre wavelength [11]).

Output powers range from megawatts to a few watts depending on the resonator configuration and on the number of longitudinal modes. The laser beam exits the rectangular waveguide with an elliptical cross section with distinctively different fast and slow axis, a large angular divergence and a close to diffraction-limited beam parameter product. The polarisation is linear, with the electrical field vector parallel to the growth direction of the quantum cascade structure, i.e., perpendicular to the substrate. QCLs can be packaged in compact modules that operate at room temperature. Electro-optical efficiencies range in the order of 10%.

3 Beam-combining techniques

Beam combining is a technique to overcome the limitations in output power of a single laser source. There are four different techniques in use today:

(i) polarisation beam combining,
(ii) spectral beam combining,
(iii) coherent spatial beam combining,
(iv) incoherent spatial beam combining.

(i) Polarisation beam combining uses, for example, the Brewster effect of uncoated surfaces or the polarisation selectivity of special coatings in order to combine two laser beams with orthogonal linear polarisation states in a common aperture. This method is restricted to two laser beams and offers thus limited power-scaling capability.

(ii) Spectral beam combining (SBC) overlays the laser beams incoherently with the spatial irradiance characteristics of a single multi-spectral aperture. Three principles can be found:
   - Several DFB QCLs are combined via a grating. The optical layout is similar to a spectrometer used in reverse. This reverse-spectrometer-type SBC requires tight control of the wavelengths of the individual QCLs and of the geometric arrangement of the set-up in order to stabilise the combined output power against vibrational and thermal disturbances [12].
   - The second technique combines the QCLs in a common external resonator. The high reflective rear facet of each QCL forms the back mirror of the resonator; the front facets of the QCLs are anti-reflection coated. The feedback is established through a common output coupler. The laser beams are coupled inside the resonator with the help of a transmission grating or a reflection grating [13]. Figure 1 depicts a sketch of SBC with a reflection grating. The wavelength of each beam is determined by the position of the QCL in the focal plane of the collimating lens. The half-wave plate serves to rotate the polarisation plane of the beams in order to use the higher diffraction efficiency of the grating in s-polarisation mode. The grating period is chosen in such a way that each beam is diffracted into the same direction (perpendicular to the output coupler) according to the grating equation. The power level of this external cavity coupling scheme is relatively insensitive against disturbances as the different laser wavelengths adjust themselves to the

imposed external conditions within the gain spectrum of the quantum cascade structures. The price to pay is an unstable spectral distribution of the output power, which makes this scheme less attractive for spectroscopic applications, unless special care is taken to ensure a high mechanical stability of the resonator configuration.

- In the third technique, the QCLs are combined in a free-space optics set-up (as shown schematically in the right part of Figure 1) or in a waveguide structure [14] employing a cascade of dichroic (multi-dielectric-coated) beam combiners.

(iii) Coherent beam combining (CBC) relies on the active or passive wavelength, amplitude and phase control of the laser beams to be combined in order to ensure proper interference in the far field. CBC may be realised in an external resonator [15] or in a common aperture [16] in which the laser beams are arranged side by side. Ideally, the beams generate an irradiance profile that corresponds to the full diameter of the radiating aperture. CBC is useful in combination with adaptive optics for long-range operations of the laser system where on-axis peak irradiance is of major concern.

(iv) Incoherent spatial beam combining (IBC) assembles the laser beams in a common aperture as in CBC but overlays the individual flux tubes in the far field without controlling the relative amplitudes or phases [17]. Consequently, the central irradiance lobe of a spatial arrangement of incoherently combined beams is wider and the peak irradiance is smaller compared to CBC. The optical realisation of IBC is straightforward. Individual QCLs are collimated using high numerical aperture micro-lenses and arranged in an aperture as illustrated in Figure 2. If necessary, the angular divergence of the beams is adapted to the illumination requirements with a telescope. With elliptical beam shapes, the orientations of the fast and slow axis introduce additional degrees of freedom to control the far-field irradiance of the beam combination. IBC is a promising technique for systems without adaptive optics (due to its aperture averaging effect) and for medium range applications. It is particularly suited for active imaging and illumination purposes where the field of view of a camera has to be irradiated. Compared to the other beam-combining techniques, IBC offers a high degree of flexibility with regard to the spectral and spatial distribution of the optical power.

4 Generating axial symmetric irradiance profiles with elliptical beams via IBC

SBC in an external cavity and CBC preserves the elliptical irradiance profile of the individual QCLs because the fast axis of the angular divergence is intrinsically coupled to the polarisation plane. In CBC, the polarisation planes of the QCLs have to be aligned in parallel to generate the final waveform through interference. In SBC with a grating, the polarisation planes should have the same orientation in order to be diffracted with similar efficiencies. Thus, in these beam-combining schemes, the fast axis of the different beams is parallel to each other and the resulting irradiance profile remains elliptical.

IBC introduces the necessary orientational degree of freedom to generate an axial symmetric irradiance profile in the far field starting from the elliptically shaped QCL beams. Reconsider Figure 2 as an example. In configurations 2 and 3, the fast axis of two QCLs facing each other is parallel and both are perpendicular to the corresponding axis of the other pair. A rotation of 90° around the optical axis of the radiating aperture does not change the arrangement. This is in contrast to configuration 1 in which the

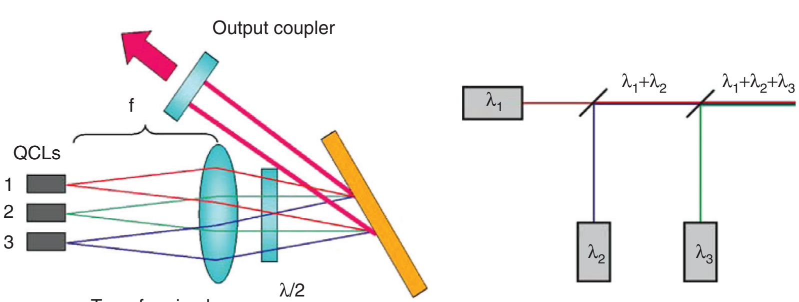

Figure 1 Illustrations of spectral beam-combining schemes in an external cavity with a reflection grating (left) and with a cascade of dichroic beam combiners (right).

fast axes of all four QCLs are parallel to each other and a rotation changes the arrangement with regard to a fixed coordinate system.

Figure 3 compares the far-field irradiance profiles of the three configurations. The parameters for each QCL are as follows: wavelength: 4 µm; slow-axis (fast-axis) full divergence angle: 20 mrad (36 mrad), M^2=1.5 for both axes. The radial distance of the QCL beam centres from the optical axis is 5 mm. The irradiance profiles are normalised by the on-axis intensity of a single QCL beam centred on the optical axis (as shown on the right side in Figure 2). The reference beam exhibits the same parameters as the off-centre beams except for the power, which is four times higher. The irradiance profile of configuration 1 resembles very closely the asymmetric profile of the single centred beam. The rotational symmetry of configurations 2 and 3 is transferred into the far field and enforces almost axial symmetrical irradiance profiles that differ slightly in peak power.

The effectiveness of IBC is measured by assessing the power of the combined beams enclosed by the cross-sectional area of a 'bucket'. This notion is similar to encircled energy well known from optic design software. The shape and size of the cross section are determined by the application and are often derived from diffraction-limited beams of uniform or Gaussian near-field irradiance profiles [18]. The circular opening of the bucket is centred on and moved along the optical (z) axis of the beam-combining aperture. In the calculations leading to the results of Figure 4, we adjust the diameter of the opening at each z-position to be equal to the $1/e^2$ diameter of the slow axis of the single centred beam introduced in Figure 2.

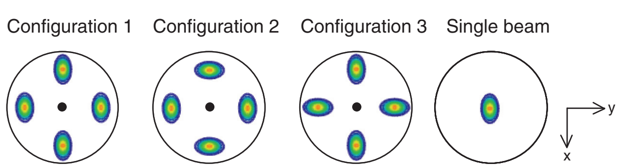

Figure 2 Illustration of the arrangement of four similar elliptically shaped QCL beams in three different configurations in a common aperture. The ellipses represent the contours of the near-field irradiance profiles. The central (black) dots indicate the optical axis. As a reference, the figure also depicts a single beam centred on the optical axis and the orientation of the (x,y) axis.

The diagrams on the left side of Figure 4 compare the irradiance values of the incoherently combined beams at different positions on the optical axis of the combining aperture. For each configuration, the on-axis irradiance of the combined beams exhibits a dead zone in the near field where the beams do not overlap. In the far field, the beam overlap is fully developed and the on-axis irradiance converges to the values of the single centred beam. In between, a local maximum of the irradiance indicates the onset of the overlap region.

The right-hand side of Figure 4 displays the power-in-the-bucket (PIB) at different positions along the optical axis. The PIB of the combined beams is normalised to the PIB of the single centred beam. In the region between the dead zones and the far field, the normalised PIB values differ among the configurations due to the different orientations of the slow/fast axis. In the far field, the combined PIB saturates at a value determined by the single beam. Compared to SBC in a single spatial mode, IBC generates similar axial and lateral irradiance profiles and PIB values in the far field. The irradiance in the near field

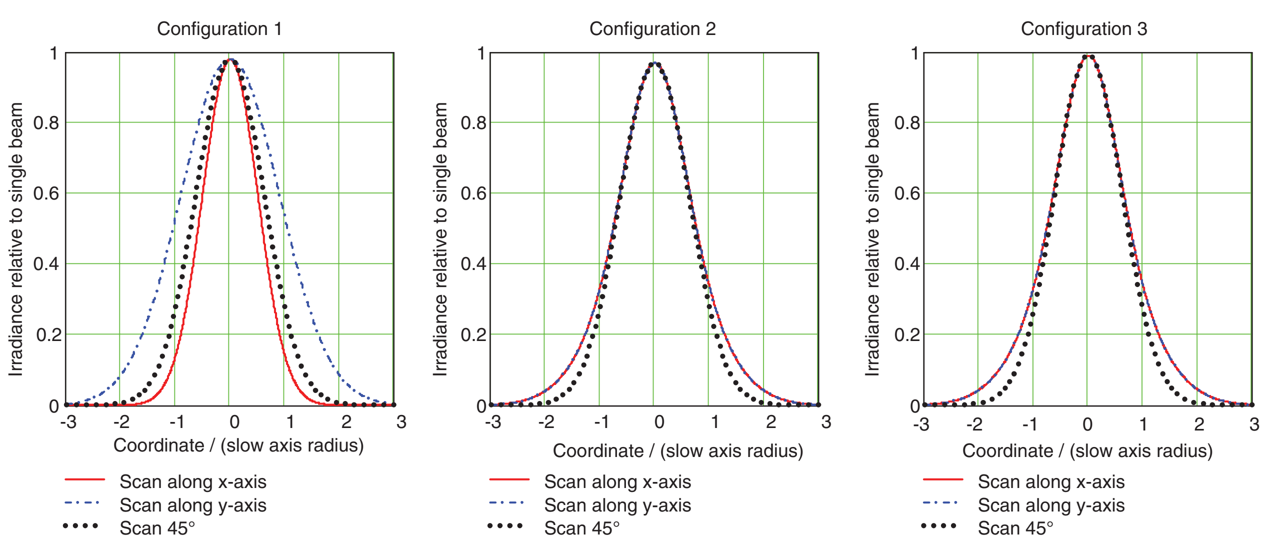

Figure 3 Far-field irradiance profiles along three directions for configurations 1, 2 and 3 of Figure 2. The abscissa is normalised to the $1/e^2$ slow-axis radius, and the ordinate is normalised to the peak irradiance of a single beam centred in the aperture.

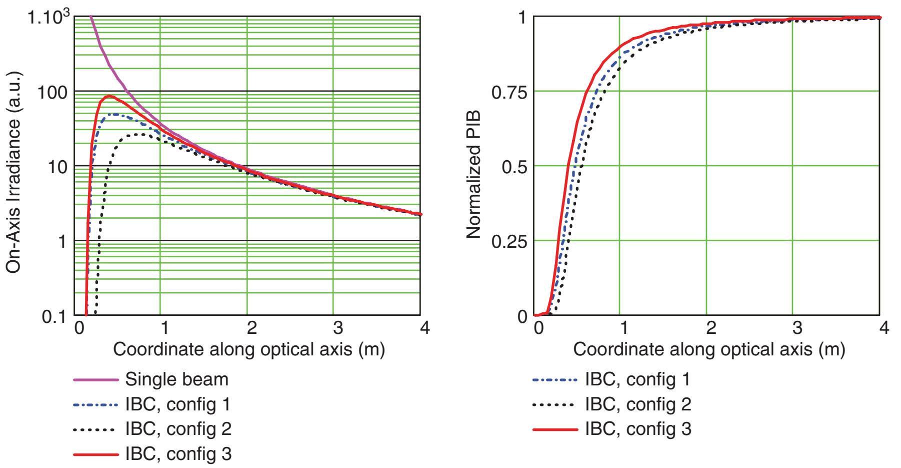

Figure 4 On-axis irradiance (left) and normalised power-in-the-bucket (right) for the three configurations introduced in Figure 2.

depends on the arrangement of the beams in the combining aperture.

5 Conclusion

The use of quantum cascade lasers (QCLs) is becoming an important part of active stand-off and remote sensing in the thermal infrared atmospheric spectral windows. The emission wavelengths can be matched to any application requirements because they are determined primarily by the laser design and not by material properties. QCLs will be employed to illuminate or heat targets of interest and to sense molecules by analysing their mid-infrared fingerprint spectra. In this letter, we summarised beam-combining schemes for the scaling of the output power of QCL modules and illustrated some options to shape the spatial and spectral power distribution in the far field using incoherent spatial beam combining.

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