Monolithic QCL Design Approaches for Improved Reliability and Affordability

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Abstract

Many advances have been made recently in mid-wave infrared and long-wave infrared quantum cascade lasers (QCLs) technologies, and there is an increasing demand for these laser sources for ever expanding Naval, DoD and homeland security applications. We will discuss in this paper a portfolio of various Naval Air Warfare Weapons Division's current and future small business innovative research programs and efforts on significantly improving QCLs' performance, affordability, and reliability.

1. Introduction

Critical applications such as proximity, sampling-based and stand-off sensing chemical sensing [1, 2], infrared countermeasures require compact, high brightness, power-scalable sources of coherent radiation in the mid- to long-infrared regime, which generally spans from 3 to 12 μm. With the latest evolutionary advances in mid-wave infrared and long-wave infrared QCLs technologies, QCLs will undoubtedly play an ever increasingly important role in homeland security and defense applications.

However, to meet the current and future needs of homeland and military defenses, there is a continuous quest for QCLs with higher output power and more agile, broader wavelength tunability. The targeted reliability and cost of a device or system for eventual DoD deployment are often afterthoughts in the development process that inevitably incurs additional cost and development delay in elevating the device's/system's performance and reliability to the required technology readiness levels. It is therefore clear to us that it would be tremendously beneficial to both the DoD and homeland security users that a monolithic, scalable semiconductor QCL platform that is scalable in power and/or broadly tunable would significantly improve by design the device's reliability, and acquisition cost and total cost of ownership. In particular, the latter cost advantages are becoming increasingly more essential in the current constraining budgetary climate and are also synergistic with the recent DoD strategic initiatives on Better Buying Power [3] for increasing acquisition efficiencies in order to "do more without more."

Until recently, most or all of the power scaling and wavelength tuning of QCLs have been implemented in a hybrid fashion where various active/passive optical elements are integrated in a subassembly. It is obvious that the there are numerous advantages to the implementation of the afore-mentioned increased functionality via a monolithic integration path instead. The few notable advantages of monolithic implementation include smaller form factor, improved performance and reliability, and lower acquisition cost and total cost of ownership. We have instituted several Navair SBIR/STTR program initiatives on creating low-cost, monolithic semiconductor-based infrared laser sources without the shortcomings of the existing QCL hybrid platforms. We will discuss in the following sections of this paper in detail those programs with paradigm-shifting initiatives.

2. Monolithic Broadly Tunable QCL

All of the tunable QCLs commercially available so far today are external-cavity tunable QCLs/ICLs which are realized in either LIttrow or Littman-Metcalf configurations (Figure 1). The laser resonator is typically set up between the antireflection (AR)-coated facet of the QCL and a diffraction grating in Littrow scheme, or a diffraction grating plus a tuning mirror in Littman-Metcalf

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set-up. In either case, wavelength tuning is achieved by means of tilting the tuning mirror or the grating via a mechanically moving mechanism.

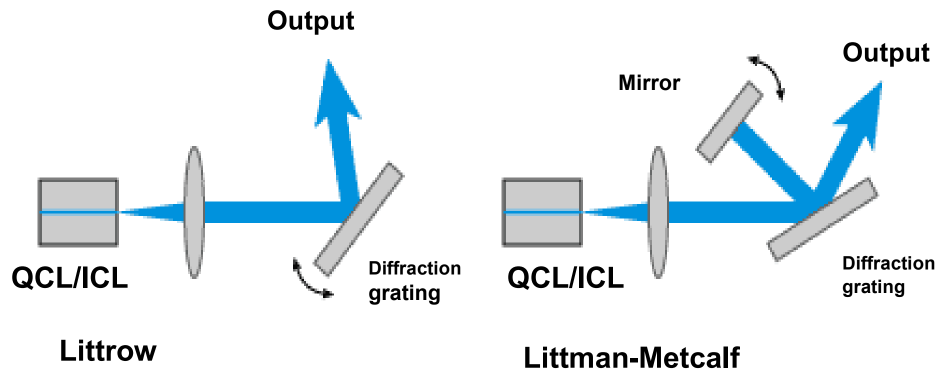

Figure 1: External-cavity tunable QCL configurations.

Even though the external-cavity tuned (ECT) QCLs [4 - 5] with relatively reasonable output power levels, and impressible tunable ranges as wide as ±14.5% tunability from the center wavelength have recently been demonstrated for sensing and instrumentation applications in laboratory settings or civilian operating environments [6, 7], there are serious performance and reliability issues in external cavity configuration that could potentially prevent the tunable technology from transitioning into military platforms. First, external cavity tunable laser devices require hybrid integration and mechanical movement of external optical elements for wavelength tuning. Hence, the optical alignments of all the elements are sensitive to shock and vibration and extreme temperature variations, thereby resulting in external cavity configurations not sufficiently robust for reliable operation in harsh military environments. Second, the entire hybrid assembly of external grating, optics and mechanical parts impacts adversely the overall laser system's size and weight and contributes to its high cost of manufacturing. Third, wavelength tuning by mechanical moving of grating or mirror is inherently slow and that would prohibit it from being deployed in some applications that need very agile wavelength tuning over a very wide spectral range. Fourth, it is also difficult to achieve tuning over a broad spectral range free of mode hopping because external-cavity laser structures require very high quality broadband, antireflection coatings with low reflectivity.

Therefore, a paradigm shift in widely tunable QCL design is necessary and field operation robustness and reliability are incorporated as part of the critical laser design parameters at the very outset of its design phase, instead of merely considering them as after-thoughts in later phases in its technology and product development process for the lasers. The goal of this program is to develop a low-cost, robust, compact, monolithic chip-based solution for a broadly tunable QCL in the mid-wave infrared (MWIR) spectral range with absolutely no mechanical moving parts that will produce high continuous wave (CW) output power >0.5 W (scalable to >10 W) with excellent beam quality of $M^2 < 1.5$, and tunability over a tunable range at least ±12% from a targeted center wavelength.

About a decade ago, short-wave infrared 1.5-μm monolithic broadly tunable lasers have been proven to successfully exceed Telcordia-468 qualification requirements by a wide margin with proven minimum 25-year operating lifetime. They are displacing the older-generation fixed wavelength lasers and are widely deployed in optical communications dense wavelength division multiplexing networks world-wide carrying live voice, data and video traffic. This class of monolithic tunable telecommunication lasers is designed in and adopted by almost every telecommunication service provider instead of ECT lasers due to its proven more superior reliability than its ECT counterparts. Even though the fundamental physics and operating principles of QCLs are different from those short-wave infrared laser diodes based on band-to-band transition, the proven field reliability of monolithic tunable laser in the telecommunications arena provides a very strong motivation and impetus for us to spearhead the development of monolithic tunable QCL without hybrid assembly of precision mechanically moving parts and critical optical elements that are inherently more rugged than its ECT QCL counterparts by design and more suited to field operations in harsh environments.

There are various examples of multiple-section DBR lasers that have been demonstrated with wide tunability [8 - 10] in the 1.5-μm regime. One of the most viable candidate configurations for monolithic tunable QCL is the tunable laser structure based on sampled-grating distributed Bragg reflector (SGDBR) architecture which has been proven to exceed the stringent reliability qualification requirements and been extensively deployed in optical communications networks in the 1.5-μm regime [10]. It is reasonable to believe that the SGDBR configuration can be carefully adapted for QCLs with appropriate modifications to provide our targeted tunable range. Figure 2 shows a schematic of SGDBR QCL structure. One of the most prominent features in this laser structure is the use of two SGDBRs as the laser cavity end mirrors which have periodic spatial modulation on the gratings in the real space domain which provides a reflection spectrum of each SGDBR mirror with periodic reflectivity maxima in the frequency domain (Figure 3(b)). This can be readily understood by looking at the reflectivity of the DBR mirror with the periodic sampling perturbation in the frequency domain. The sampled grating is a conventional grating at the appropriate wavelength multiplied by a sampling function (Figure 3(a)). In the frequency domain, the Fourier components of the SGDBR can be obtained by convolving the single Fourier component of the grating at the Bragg wavelength with the comb of Fourier components in the sampling function, resulting in a comb of Fourier components centered at the Bragg wavelength (Figure 3(b)), where z_1 is the length of the grating burst and z_0 is the length of the grating sampling period.

As shown in Figure 3(b), the reflectivity comb maxima of a SGDBR are separated by $2\pi/z_0$. Therefore one could design the front and back SGDBRs with slightly different z_0 values, thereby producing reflection maxima with different wavelength periods created for both mirrors. Thus, if a certain reflection maximum from one mirror is aligned with a maximum in the second mirror, all the other maxima are misaligned as shown in Figure 4. The product of the two mirror reflectivities, which determines the cavity loss, will only have a single maximum and the laser will therefore lase at a single frequency with excellent side mode suppression ratio at the wavelength at which the pair of maxima is aligned. Besides satisfying the cavity loss condition by aligning the reflectivity maxima, the round trip cavity phase condition for lasing needs to be satisfied as well and this is accomplished by adjusting the phase in the phase section.

If the index of one SGDBR is tuned differently from one another, adjacent maxima will eventually line up. If the periodicities of the maxima are slightly different by design, only a small index difference of a fraction of 1% would be possible to switch the alignment across various different reflection maxima, thereby enabling tuning over the entire amplification range of the gain section of the laser. It is worth pointing out that although the refractive indices of the SGDBRs of the SGDBR lasers in 1.5-μm fiber optics communications band are caused by carrier injection into the mirrors, it is more efficient and effective to induce the needed refractive index changes in SGDBRs in SGDBR QCL structures by means of temperature changes of the SGDBR materials because of high free carrier absorption in the MWIR spectral range. As shown in Figure 2, another advantage of the SGDBR QCL structure is that a power amplifier can be monolithically integrated with the tunable laser structure in a master oscillator power amplifier configuration so as to significantly boost the laser output power while still maintaining the single-frequency high beam quality across all the accessible wavelengths.

The participants of this program in its phase II are EOS Photonics/Harvard University and MP Technology/Northwestern University. We will discuss and present the program's latest development and program details.

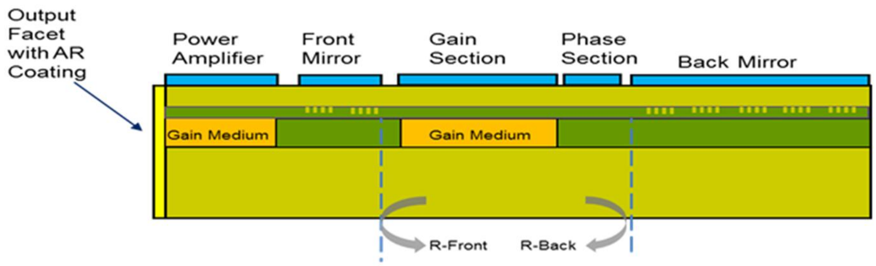

Figure 2. A device schematic of monolithic broadly tunable QCL structure.

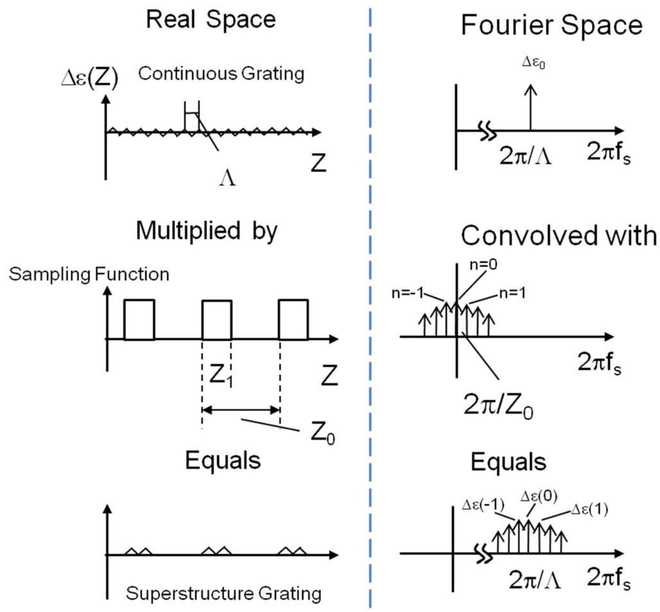

Figure 3: (a) Sampled grating is equal to continuous grating multiplied by the periodic sampling function in real space domain. (b) Convolving the grating spectrum with that of that of the sampling function yields the Fourier spectrum of the sampled grating. After [10].

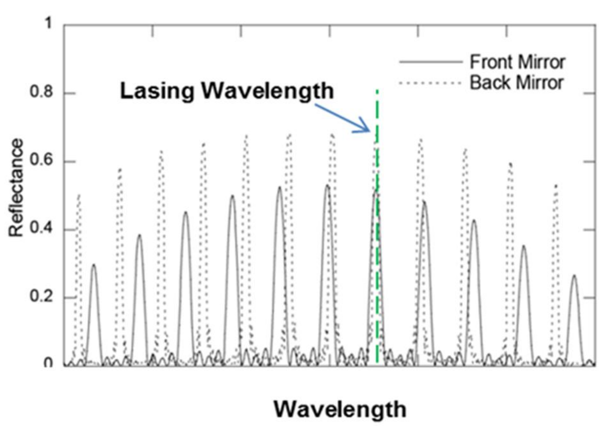

Figure 4: Schematic representation of the individual SGDBR reflectivities R_{Front} and R_{Back}. The emission wavelength corresponds to the position at which two maxima overlap.

3. Monolithic Beam-Combined QCL Array

Individual QCLs emitting at ~ 4.6 micron with 3 Watts CW output power and wall-plug efficiency close to 15% have been recently demonstrated [11]. To further increase the output power of a single QCL to meet the future needs of the military, the idea of increasing the output by increasing the length and/or width of the laser strip is impractical due to limiting factors such as gain saturation, thermal issues caused by its poor thermal conductance and degradation of output beam quality. To increase the aggregate output power level of the laser sources while simultaneously maintaining near-diffraction-limited beam quality, one can combine the multiple laser beams using coherent beam combining (CBC) or spectral beam combining (SBC) [12]. Most or all of CBC or SBC schemes that have been demonstrated today in the shorter wavelength and/or MWIR ranges require hybrid integration of laser array with external optical elements and/or electronics, and hence a more cumbersome, costly and less reliable platform for demanding field applications. The goal of this program is to develop a cost-effective platform that enables monolithic beam combining (MBC) of high power CW QCL arrays. The objective is to develop a completely MBC solution that comprises of QCL array, and compact passive combiners that produce CW output power > 15 W (scalable to 100 W) with excellent beam quality of $M^2 < 1.5$ and wall-plug efficiency over 10% at a targeted MWIR wavelength.

One of the most straightforward approaches to beam-combine multiple QCLs for power scaling is to combine a spatially separated QCLs in an array each with well-defined single wavelength and combine them using a wavelength-sensitive beam combiner. Lee et al. [13, 14] assembled a linear monolithic array of 32 distributed feedback (DFB) QCLs with broad gain bandwidth using bound-to-continuum active region for a demonstration of SBC (Figure 5). Each of the laser elements within the array was designed with a different emission wavelength via a different DFB grating pitch and was individually addressable and driven by a microelectronic controller. Beam combining is accomplished by a suitably placed grating and transform lens that overlap the beams from each laser in both the near-field and far-field. The challenges in implementing the SBC in this program is to implement the QCLs and the functionality of the external lens and grating all on a monolithic semiconductor substrate.

The participants of this program in its phase II are Intraband LLC/University of Wisconsin and EOS Photonics/Lincoln Lab. We will also discuss and present the program's latest development and details.

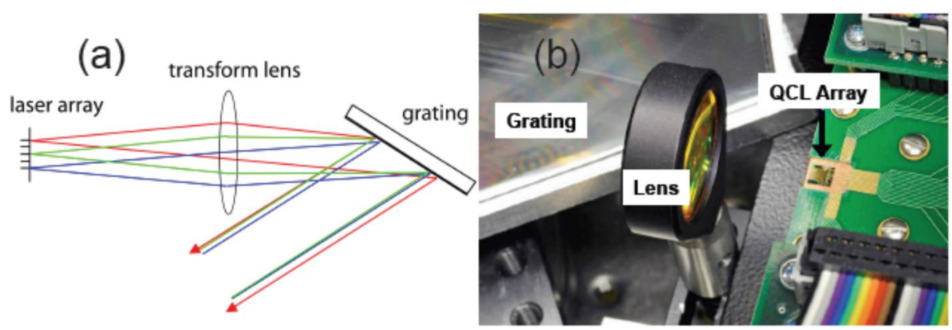

Figure 4: (a) Spectral beam combining of a DFB QCL array. (b) Actual spectral beam combining of the DFB QCL array. After [10].

4. Surface emitting QCLs

Monolithic surface-emitting (SE) semiconductor lasers hold promise for significant advantages over edge-emitting lasers in terms of both reliable operation and manufacturing cost. Device-failure modes that are triggered by high facet optical-power densities and/or temperatures, which, in turn, generally limit the reliable output power of edge-emitting lasers, are thus eliminated. Therefore, this is a new program dedicated to taking the targeted performance and reliability improvement and, more importantly the affordability of MWIR QCLs via innovative MWIR laser design strategy to the next level.

Commercialization of near-infrared vertical cavity surface emitting lasers (VCSELs) has led to ultralow-cost sources in the market. The substantial cost reduction of the surface emitting laser diodes is primarily achieved via the elimination of a few high-cost, low-yield, labor intensive fabrication and packaging steps such as wafer lapping, cleaving, dicing, facet-coatings, and chip bonding, etc., which amount to 60 to 75% of the total cost of manufacturing the edge-emitting laser diodes. Using the similar design and manufacturing paradigm in the near-infrared SE laser diodes, we are confident that the successful development of SE MWIR QCLs or coherent beam-combined SE QCL arrays can further improve the affordability of QCLs because of the ability to perform game-changing wafer-level fabricating and testing, without the need to separate and package the individual chips prior to testing.

Extension of the VCSEL technology to the MWIR QCL structure is proven to be very challenging due to its unique emission polarization caused by the inter-subband transitions not compatible with VCSEL's distributed Bragg reflectors (DBRs) [15], and hence a more innovative monolithic output coupler structure will have to be integrated with the QCL structure to enable surface emission. The goal of this program to develop an innovative low-cost-by-design, power-scalable, chip-based platform solution that enables surface emission from a single aperture with CW output power > 15 W and outstanding beam quality of $M^2 < 1.2$ from either a single SE QCL or monolithic coherently beam-combined SE QCL array at the targeted MWIR wavelength.

The program is in its Phase I. The participants in this Phase I are MP Technology/Northwestern University, EOS Photonics/Harvard University and Intraband LLC/University of Wisconsin. We will discuss various SE QCLs design approaches being researched in this program during the presentation.

5. Conclusion

QCLs have secured a strong foothold in the marketplace as the light sources of choice for defense and homeland security applications, such as chemicals, explosives and gases sensing, and infrared countermeasure in MWIR spectral ranges. We have presented in this paper several NAVAIR program initiatives on innovative technology and product developments of completely monolithic designs of QCLs with targeted enhanced functionalities/performances but also with the unparalleled simultaneous benefits of built-in improved reliability and costs reduction.

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