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ABSTRACT
Quantum cascade lasers are, by far, the most compact, powerful, and spectrally pure sources of radiation at terahertz frequencies, and, as such, they are of crucial importance for applications in metrology, spectroscopy, imaging, and astronomy, among many others. However, for many of those applications, particularly imaging, tomography, and near-field microscopy, undesired artifacts, resulting from the use of a coherent radiation source, can be detrimental. Random lasers can offer a concrete technological solution to the above issue. They, indeed, maintain a high degree of temporal coherence, as traditional lasers, while only exhibiting low spatial coherence, which can allow for the prevention of coherent artifacts, such as speckles. In this study, we report on the development of one-dimensional THz-frequency random wire lasers, patterned on the top surface of a double-metal quantum cascade laser with fully randomly arranged apertures, not arising from the perturbation of a regular photonic structure. By performing finite element method simulations, we engineer photonic patterns supporting strongly localized random modes in the 3.05–3.5 THz range. Multimode laser emission over a tunable-by-design band of about 400 GHz and with ∼2 mW of peak power has been achieved, associated with 10° divergent optical beam patterns. The achieved performances were then compared with those of perturbed Fabry–Perot disordered lasers, showing continuous-wave operation in the 3.5–3.8 THz range with an order of magnitude larger average power output than their random counterpart, and an irregular far field emission profile.

The terahertz (THz) region of the electromagnetic spectrum, commonly defined as the frequency range from 100 GHz to 10 THz, is of great technological and applicative interest because it connects the domains of optics and electronics, thereby offering a plethora of opportunities for developing devices, components, and systems with schemes and functionalities at the intersection between the two different domains. It also plays an important role in a number of fields including astronomy, biomedicine, chemical detection, security screening, cultural heritage, high-resolution spectroscopy, metrology, imaging, and tomography.

Among the available far-infrared sources, quantum cascade lasers (QCLs) are the most performing emitters of THz-frequency radiation. They, indeed, combine compactness, a broad (>1 THz) emission spectrum, resulting from ultra-broad gain bandwidths engineered by design, stable continuous-wave (CW) operation, high (1–2 W) output powers, intrinsically high spectral purity (100 Hz intrinsic linewidths), and the possibility to operate as stable optical frequency comb synthesizers.

Usually, THz QCLs suffer from the large divergence of the emitted optical modes, arising from deep sub-wavelength emission facets and the lack of spectral selectivity in the most conventionally employed Fabry–Perot cavity geometry, in which the electromagnetic field is deeply delocalized. A lot of effort has been, therefore, invested, in the last decade, to overcome the above limitations, developing and implementing specific photonic designs on the top surface of the laser cavity to control the emission spectrum and the beam shape, by selecting the dominant intra-cavity modes responsible for feedback and light extraction.
Periodic patterning has been successfully exploited in combination with miniaturized THz QCLs to tailor the emission frequency, the optical power, the beam divergence and direction in both photonic crystals, distributed feedback (DFB) lasers, and resonators having different degrees of disorder, such as aperiodic one-dimensional (1D) and bi-dimensional (2D) lattices, quasi-crystals, and random lasers.

Disordered photonic systems exhibit unique and fascinating properties because of the co-existence of Bragg scattering on a sparse reciprocal lattice and Anderson localization of light arising from the disorder. As such, the propagation of light in disordered media has raised significant research interest, both theoretically and experimentally.

Laser action in random systems has been demonstrated in many different classes of lasers such as powder crystals, dye lasers, and, most recently, in semiconductor lasers, mostly in the visible region. The possibility to achieve Anderson localization, combined with the inherently low spatial coherence and high temporal coherence, makes this class of lasers appealing for many practical applications in which the lack of coherent artifacts can play a major role.

Recently, random lasing has been also demonstrated in electrically pumped semiconductor heterostructure lasers, first in the mid-infrared, and most recently at THz frequencies. Typically, a bi-dimensional resonator architecture is employed, which, due to the large resonator volume involved, inherently limits the device electrical-to-optical power conversion efficiency (wall-plug efficiency). There is presently only one experimental report of 1D-disordered THz QCLs, in which lasing is due to localized modes arising from a periodic-on-average random photonic structure, i.e., from the perturbation of a period photonic structure.

Here, we conceive and devise a new class of 1D electrically pumped random lasers at THz frequencies. The core structure is the quantum cascade laser in which a novel concept for localizing the electromagnetic field over much shorter lengths has been exploited. A series of sub-wavelength (λ) scatterers with an average spacing varied between λ/10 and λ/5 is lithographically imprinted on the top laser surface and defines a feedback grating which, very differently from previous reports, does not rely on the perturbation of an ordered structure. Indeed, the apertures are uniformly distributed on the top metal cladding, while only discarding those that fall under a minimum distance to avoid overlapping, thus leading to a much higher degree of disorder. Consequently, the resulting electromagnetic modes are not dependent on the perturbations induced on an underlying ordered pattern but must rather entirely emerge from the specific choice of a disordered sequence of point-like emitters. Since Anderson localization is favored in low dimensional systems, a sufficient degree of disorder in a 1D QCL resonator is expected to lead to random lasing, even in the absence of a proper photonic bandgap.

Our one-dimensional random resonator exploits an array of open slits, lithographically patterned on the top metal surface of the laser [Fig. 1(a)]. The array induces a local spatial modulation of the refractive index [Fig. 1(b)], which determines the photon scattering
mechanism for light feedback and extraction. The laser waveguide is 110 μm wide and 1.63 mm long, including absorbing boundaries, which are 10 μm and 65 μm wide, per side, on the transversal (y) and longitudinal (x) directions, respectively. The metal absorber consists of a thin (10 nm thick) chromium layer, deposited on the top of the QCL heterostructure with the specific purpose to suppress undesired Fabry–Perot modes and high-order lateral modes. The whole patterned area is 1.4 mm long and 90 μm wide, and a 50 μm long gold area is left unpatterned for wire bonding. The apertures are defined on the top metal plate trough a combination of laser writing, reactive ion etching, metal deposition, and lift-off, and their size in the direction transversal to the laser bar [L in Fig. 1(e)] has been set to 3/4 the width of the top gold plate.

The random pattern is generated via a custom Matlab code, employing a random function. Each rectangular slit is 5 μm wide, at variable distances, being the minimum set to 5 μm.

Considering a two-dimensional effective index model for the case of a desired photon frequency of about 3.2 THz, the air slit can be described with an effective refractive index $n_B = 2.6$ while, in the metal-covered area, the effective refractive index is $n_A = 3.6$.

Full 3D simulations of the geometries are performed with COMSOL Multiphysics in order to extract the average quality factors, $Q_{3D}$, of the cavity modes and select only those patterns that determine the existence of localized modes with $Q_{3D}$-factors high enough to reach laser emission.

The GaAs/AlGaAs-based active region heterostructure is described with a refractive index $n_1 = 3.6$, as shown in Fig. 1(b). The 10-nm-thick Cr layer, covering the ridge external border, is modeled as a boundary layer between the underneath heterostructure and air, with a complex refractive index $n_2 = 37 + i87$ based on time domain spectroscopy data present in the literature. The top and bottom metal claddings of the laser are described exploiting the perfect electric conductor (PEC) conditions, and the laser is surrounded by a finite volume of air with $n_{Air} = 1$. In order to mimic light propagation in free space, scattering boundary conditions (SBCs) are implemented at the outer surface of the air volume.

Figure 1(c) shows a prototypical simulation of one localized electromagnetic mode located at 2.89 THz. The evolution of $Q_{3D}$ over the employed QCL gain bandwidth [Fig. 1(d)] unveils the lack of pseudo-bandgaps in the investigated frequency range, and the presence of some modes, located between 2.8 THz and 3.1 THz, showing $Q_{3D}$ well above the average.

The QCL heterostructure employed in this work is based on a three quantum well architecture, which defines a 550 GHz wide gain bandwidth peaked at 3.2 THz. The optical power performances in a standard double metal Fabry–Perot configuration are shown in Ref. 19.

In order to extract the relationship between filling factors (FFs, defined as the ratios of the scatterers area over the total ridge area) and random lasing, we conducted a statistical study by simulating a

![FIG. 2](image-url)

**FIG. 2.** (a) Frequency of occurrence of localized optical modes having high quality factor and low gain threshold, expected to provide random lasing, as a function of the filling factor. The frequency of occurrence is obtained for each filling factor by performing the simulation of 10 random sequences of slits. (b) Voltage–current density (V–J) and light–current density (L–J) characteristics measured at a heat sink temperature of 15 K while driving individual random QCLs, having different filling factors (FF), in pulsed mode (pulse width 1 μs; pulse frequency 100 kHz) via lock-in detection of a circular pyroelectric detector with 3 mm diameter. Optical power scales were corrected to account for the detector collection efficiency (integrating the measured optical power over the corresponding three-dimensional far-field intensity pattern) and the absorption of the polyethylene cryostat window (75%). The LJ curve collected at a lattice temperature of 105 K is also shown on the graph for the device having FF = 23%, where the emitted power has been magnified by a factor of 5. (c) Extrapolated peak optical powers plotted as a function of the filling factor. (d) Three-dimensional simulation of the out-of-plane emission of the optical modes of panel 3f, derived by applying the Stratton–Chu method to its near-field emission.
large number of devices with different random sequence of slits and with FF ranging between 4% and 30%. For each simulated device, we calculated the eigenmodes, the quality factors, and the threshold gains to check for the presence of any eventual localized mode supporting lasing. The results [Fig. 2(a)] show a low probability of random lasing for low filling factors, which increases smoothly as FF is increased. This is expected considering the related increase in the number of random scatterers and from the fact that for very high filling factors, the patterns approach a periodic arrangement of slits.

Accordingly, a set of wire lasers having filling factors (FFs), ranging between 15% and 26%, has been designed and fabricated. For each individual filling factor, many random sequences have been generated, using the same sequence of parameters but different “rolls” of a random number generator; then, two different random sequences of scatters have been selected from the simulations and implemented on the top metal surface (see the section titled Methods).

A scanning electron microscope (SEM) picture of a fabricated device is shown in Fig. 1(e).

The voltage–current density (V–J) and the light–current density (L–J) characteristics [Fig. 2(b)] show that all devices share a common threshold current density ($J$) of $\sim 425 \text{ A/cm}^2$, similar to that of the reference Fabry–Perot lasers ($410 \text{ A/cm}^2$). Very differently to what we have previously reported for 2D random lasers, fabricated by employing the same QCL heterostructure,\textsuperscript{19} the peak power output does not show a monotonic dependence from the filling factor, which indeed increases from FF = 15% to FF = 23%, reflecting the larger output losses and then starts decreasing; all lasers emit peak optical powers of about 1–2.2 mW, as shown in Fig. 2(c). It is worth mentioning that the achieved peak optical powers are more than a factor of 25 larger than that of previously reported 1D random lasers,\textsuperscript{19} with a three order of magnitude improvement in the associated wall plug efficiency, despite the active region design leads to comparable output powers in a standard double-metal waveguide configuration. This suggests that such an improvement can be mainly ascribed to photonic pattern itself. The devices exhibit laser emission up to a lattice temperature of 105 K, with a related peak optical power of 0.1 mW [Fig. 2(b)].

Although the FF affects the power output, it does not influence the threshold current density. This behavior is in agreement with what was observed already in 2D THz random lasers\textsuperscript{17} and very different from previously studied mid-IR random lasers, where an increased scattering density primarily leads to a higher Q factor and, thus, to a reduced laser threshold.

![Fig. 3](https://example.com/fig3.jpg)

**FIG. 3.** (a–d) Far-field intensity patterns measured in pulsed mode (pulse width 1 $\mu$s; repetition rate 100 kHz), while driving the laser at a current corresponding to the maximum laser power output, at a heat sink temperature of 15 K for a set of random lasers having different FF of (a) 15%, (b) 19%, (c) 23%, and (d) 26%. The two different far-fields for in each individual inset (a), (b), and (c) refer to the two different random patterns fabricated for each filling factor. Experiments were performed by scanning a pyroelectric detector on a sphere centered on the laser surface having a radius $r = 5.5$ cm; (e)–(h) Fourier transform infrared spectra of the lasers measured in pulsed mode (pulse width 1 $\mu$s; repetition rate 100 kHz), at a heat sink temperature of 10 K in a liquid-helium-cooled cryostat, at different operating voltages. The shown spectra refer to (e) a laser with FF = 15% [top of Figs. 2(a)], (f) FF = 19% [top of Fig. 2(b)], (g) FF = 23% [top of Figs. 2(c)], and (h) FF = 26%. As the bias is increased, higher frequency modes appear and dominate the spectra.
We then derived [Fig. 2(d)] the far-field emission profile of a prototypical random laser (FF = 19%) from the Stratton–Chu method applied to the near-field emission. Although such a simulation does not allow accounting for phenomena as the gain mode competition or non-linear effects that deeply influence the far-field profiles, it can still provide a qualitative idea of the expected emission profile.

The corresponding far-field intensity profiles were measured by scanning a pyroelectric detector mounted on motorized stage at a distance of 5.5 cm from the laser surface, across a spherical aperature. The collected intensity profiles clearly unveil the random nature of the emission [Figs. 3(a)–3(d)]; indeed, by varying the patterned random scatterers geometry, the devices show strongly different far-field patterns but copies of the same random structure feature a very consistent and well reproducible intensity profile.

In all cases, a 50° divergence along the $\Theta$ direction [see reference axes in Fig. 1(a)] has been retrieved as the $\Theta$ axis reflects the geometrical features in the transversal, $y$-direction, common to all samples. In fact, it roughly corresponds to the divergence of a Gaussian beam with a waist $w = 55 \mu m$, half the transversal size of the devices, at the frequencies of interest (3.0–3.4 THz).

On the contrary, the $\Phi$ dependency of the emission is a distinctive characteristic of each individual random pattern, with an associated divergence ranging from 10° to values larger than 45° and with a great variability in the number and direction of the main lobes.

The FTIR emission spectra [Figs. 3(e)–3(h)] show a spectral coverage of 400 GHz between 3.0 THz and 3.4 THz, with a variable number of random modes, up to 10. The irregular frequency spacing of the emitted peaks confirms that they cannot be associated with Fabry–Perot modes, which, as expected, are efficiently suppressed by the chromium surrounding absorbers, and that the feedback, indeed, arises by the random scattering with the apertures. Notably, at increasing electric fields, there is a clear, albeit small, shift toward higher frequencies. Single peaks show a tuning of about 5 GHz from threshold to maximum voltage, while globally the normalized intensity of the high frequency peaks goes up as the voltage is increased. We also note that the measured frequency band matches with that of 2D random lasers based on identical active region heterostructures and coincides with the peak gain bandwidth of the active region, showing that the feedback mechanism of random lasers is inherently broadband.

In order to verify that the lasing modes are, indeed, localized modes whose feedback is provided by the random scattering, we fabricated a second set of devices employing the same active region but a different cavity design [Fig. 4(a)]. The cavity length was set to 0.7 mm, and the side Cr absorbers on the longitudinal direction have been reduced from 65 μm to only 10 μm.

The rationale, corroborated by simulations [Fig. 4(b)], is that, under this geometry, the lateral absorber causes a very inefficient mode suppression; consequently, the dominant feedback mechanism is expected to be the reflection from the laser un-cleaved...
facets, which, even if not defining a high quality factor mirror-like, Fabry–Perot cavity, can contribute to the intracavity feedback and induce light out-coupling. In this context, we will refer to these modes as "surface-emitting perturbed Fabry–Perot modes." Since the optical feedback in this latter set of devices is not expected to be completely controlled by the scattering with the apertures, we explored a broader range of filling factors, from 4% to 30%, to verify how they influence the laser emission dynamics. The Fourier transform infrared spectra, shown in Fig. 4(c), confirm that lasing modes are, indeed, perturbed Fabry–Perot modes since they are mostly composed by a set of equally spaced modes, separated by integer multiples of the fundamental longitudinal frequency of the cavity, with a few limited clusters of unevenly spaced modes around.

Furthermore, only the devices with small filling factors (in the range 4%–11%), showed lasing, with a distinct decrease in the emitted optical power as the filling factor is increased [Fig. 4(d)]. This is a clear indication of the different feedback mechanisms between the two sets of samples: as the filling factor is increased, the quality factor of a Fabry–Perot mode goes down, eventually preventing laser action. Interestingly, though, the samples with high filling factors from the second set do not show lasing, contrary to what was observed with the first set of random lasers. As a last clear difference, this second set of lasers showed far-field profiles that, although still similar to those shown before in the striped-like pattern, are notably much more uniform, if one looks to the relative intensity of each stripe [Fig. 4(f)]. Furthermore, although significantly weaker (by more than one order of magnitude), this class of lasers also shows in-plane emission at low elevation from the horizontal (less than 40°), which could be attributed to standard Fabry–Perot light extraction, with identical spectral dynamics as retrieved from the measured FTIR spectra.

It is worth mentioning that, in this latter class of perturbed Fabry–Perot lasers, continuous-wave operation has been reached with an average power output of 1.3 mW [Fig. 4(c)], an order of magnitude larger than that of the previous set of devices and a correspondingly 0.03% wall-plug efficiency [Fig. 4(d)]. In pulsed mode, the wall plug efficiency reaches 0.12%. However, purely random 1D lasers allow for a much richer emission spectrum as well as much lower divergence, as can be easily seen from the comparison between the far field intensity patterns of Figs. 3(a)–3(d) and 4(f). Note that the far field pattern of Fig. 4(f) has been collected by keeping the laser surface oriented, an angle of about 40° with respect to the scanning detector main axis.

In conclusion, we have demonstrated 1D THz random QCLs based on completely random photonic patterns, which, very differently from previous approaches, are not conceived as a perturbation of a regular structure. Laser emission with optical powers up to 2 mW has been achieved, with wall plug efficiencies three orders of magnitude larger than that retrieved in the only experimental report of 1D aperiodic THz QCL lasers. Rich multimode emission over a 400 GHz wide bandwidth, with up to ten modes, and a beam divergence strongly affected by the selected random sequence and FF have been demonstrated. The random nature of the optical modes can be perturbed by varying the absorbing boundaries, leading to a mixing between random modes and intense perturbed Fabry–Perot-like cavity modes, inducing continuous-wave multimode surface emission with up to 8 mW of optical power.

METHODS

The GaAs/Al_{0.15}Ga_{0.85}As QCL heterostructure was grown by molecular beam epitaxy on an undoped GaAs substrate. The active region features a three-quantum-well architecture, with a single extractor well. The layer sequence is 5.5/11.0/1.8/11.5/3.8/9.4/4.2/18.4 (in nm), where Al_{0.15}Ga_{0.85}As layers are shown in bold face, GaAs in roman font, and the underlined number indicates a Si-doped layer with a density of 2 \times 10^{16} cm^{-3}. The active region growth is terminated by a 700-nm-thick highly doped (2 \times 10^{16} cm^{-3}) GaAs contact layer, with an Al_{0.5}Ga_{0.5}As etch-stop layer on the top. After growth, Au–Au thermocompressive wafer bonding of the QCL wafer onto an n^{+}-GaAs carrier wafer was performed. After selective wet etching of the host GaAs substrate and the Al_{0.5}Ga_{0.5}As etch-stop layer, the active region was coated with a top metal layer of Cr/Au (8 nm/150 nm). The resonators were fabricated by keeping fixed the laser ridge width W = 110 μm and the ridge length L = 1.6 mm for the first set of devices and 0.7 mm for the second set. By using optical lithography, the sample surface was patterned with a random sequence of air slits. The first set of devices has been patterned with 5 μm wide slits, randomly arranged with a minimum distance between slits of 5 μm, varying the filling factor between 15% and 26%.

For the second set of devices, both the FF and slit width have been varied, achieving lasing with the following patterns, in which, starting from the distance from one end of the laser, each number indicates the distance from one slit to the previous one:

- #1 (slit width 10 μm, FF 4%): 157.7, 160.6, 154.3, 80.7
- #2 (slit width 8 μm, FF 5%): 165.5, 108.7, 129.5, 11.4, 38.7, 84.7
- #4 (slit width 10 μm, FF 7%): 103.0, 25.0, 88.0, 19.5, 185.0, 63.0, 62.0
- #5 (slit width 8 μm, FF 7%): 140.0, 21.5, 33.5, 57.8, 77.7, 42.7, 34.3, 12.0, 137.8
- #6 (slit width 8 μm, FF 11%): 83.5, 39.2, 30.1, 17.9, 38.4, 18.8, 65.6, 58.2, 14.7, 20.9, 75.2, 20.8, 25.3, 20.6

The 700-nm-thick n^{+} top contact layer was completely removed below the etched slits by means of an inductively coupled plasma-reactive ion etching (ICP-RIE) process so that cavity losses are reduced and light extraction is optimized. An external 10-nm-thick Cr border was fabricated on the active region using optical lithography, surrounding the gold top metal region, and implementing strongly absorbing boundary conditions. Under the Cr border, the n^{+} top contact layer was not etched away to enhance the suppression of modes extending toward the edge of the resonator. A final ICP-RIE process was required to etch down the ridge with vertical sidewalls. Finally, individual devices were cleaved and indium-soldered onto a copper sub-mount and wire bonded at the two edges of the long side of the ridge, in order to minimize the perturbation of the far-field emission profile by the gold wires.

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