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Integrated terahertz optoelectronics

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ABSTRACT

Currently, terahertz (THz) optical systems are based on bulky free-space optics. This is due to the lack of a common platform onto which different THz components, e.g., source, waveguide, modulator and detector, can be monolithically integrated. With the development of THz quantum cascade laser (QCL), it has been realized that the QCL chip may be such a platform for integrated THz photonics. Here, we report our recent works where the THz QCL is integrated with passive or optoelectronic components. They are: 1) integrated graphene modulator with THz QCL achieving 100% modulation depth and fast speed; 2) phase-locked THz QCL with integrated plasmonic waveguide and subwavelength antennas realizing dynamically widely tunable polarizations.

Keywords: terahertz, optoelectronics, quantum cascade laser, photonics integrated system, metasurface

1. INTRODUCTION

The terahertz (THz) frequency region of the electromagnetic spectrum (~0.3 THz to 10 THz) has potential for a number of diverse applications ranging from non-destructive imaging¹ and spectroscopic sensing,² through to ultra-high bit rate wireless communication.³ Research in this region of the spectrum has undergone significant development over the last two decades, and the development of devices such as the quantum cascade laser (QCL)⁴ and the THz quantum well infrared photodetector (THz QWIP)⁵, together with the introduction and application of new materials such as graphene and metamaterials, are bringing THz technologies closer to more widespread application.

An optical modulator is a key component widely used for beam manipulation, imaging, optical communication, and active mode locking in other parts of the electromagnetic spectrum. However, the development of fast and efficient THz modulators is in its infancy, compared with the significant advances made in THz frequency lasers and detectors. Attempts to fabricate THz amplitude modulators have so far focused on semiconductor heterostructures containing a two-dimensional electron gas (2DEG) in which electrons can be accumulated or depleted by an applied gate voltage.⁶ However, the modulation depth of such devices is initially found to modulate the THz amplitude by only a few percent, although through the incorporation of metamaterials or plasmonic structures that enhance the interaction between the THz radiation and the 2DEG,^{7,8} a modulation depth of 30% was achieved more recently. A more promising material for efficient THz modulation is graphene⁹. Its carrier concentration can be electrically tuned to much higher concentration than the 2DEG. Recently a modulation depth of ~15% was achieved in the 570 – 630 GHz frequency band through electrical gating of a graphene sheet,¹⁰ and this was increased to ~64% through use of plasmonic or cavity structures. However, further increase of the modulation depth has proved difficult, unless by stacking multiple graphene layers.¹¹ In addition, all the graphene modulators to date were studied as isolated components, with typically large active areas (tens of mm²) required to facilitate optical alignment. The consequent large time constant of the effective RC circuit of the device limited the modulation speed of such graphene modulators to only ~13 MHz.¹² To explore the full potential of graphene, the monolithic integration of a graphene modulator with a THz radiation source is a promising solution. The benefits are three-fold: first, miniaturization will increase the modulation speed owing to reduced parasitic capacitance and resistance of the device; second, a larger modulation depth may be achieved as a stronger interaction of the THz radiation with the graphene layer is possible; and, finally, the integration eliminates one stage of optical alignment and the associated bulky mirrors or lenses.

Another important aspect of optical radiation is polarization. The ability to manipulate the polarization states of radiation has a breadth of applications across the electromagnetic spectrum including spectroscopy, imaging, and communications. Manipulation of the polarization state of light usually relies on external, bulky, optical components, such as wave plates and polarizers. However, these do not lead to system miniaturization and fast operation, and many such components are

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lossy over specific wavelength ranges (e.g., marketed terahertz (THz) frequency continuous polarization converters have a transmission $< 30\%$)¹³. Therefore, there is an essential need to develop low loss, monolithic devices with controllable polarization. Previously, it has been demonstrated that the polarization state of spin-polarized lasers¹⁴ and light-emitting diodes¹⁵ can be tuned by varying the amplitude or direction of an applied external magnetic field, achieving a degree-of-circular-polarization (DOCP) of up to 50%. Furthermore, a DOCP of 98% was achieved in quantum cascade lasers (QCLs) with built-in antennas^{16,17} for selected far-field regions of the emission, albeit pre-determined by the device fabrication process. However, monolithic light sources have yet to be demonstrated in which electronic tuning leads to a widely and dynamically tunable polarization state, and a high DOCP.

Here, we report our recent works on the above two aspects. First, we introduce the realization of graphene modulators integrated with surface-emitting concentric-circular-grating (CCG) THz quantum cascade lasers (QCLs)¹⁸ for achieving a 100% modulation depth with a fast modulation speed¹⁹. Then, we demonstrate that the polarization of terahertz (THz) frequency radiation can be continuously tuned electronically from linear to circular polarization by monolithically integrating in-plane metasurfaces with two phase-locked semiconductor-based THz quantum cascade lasers (QCLs). Moreover, the metasurfaces – metal antenna arrays in this case – also act as efficient beam collimators, yielding a collimated beam divergence of $\sim 10^\circ \times 10^\circ$.

2. RESULTS AND DISCUSSION

2.1 Integrated THz graphene modulator

Fig. 1(a) shows a schematic illustration of the integrated device, which consists of an underlying surface-emitting CCG THz QCL with a graphene modulator, the Fermi level of which can be dynamically tuned by a voltage V_{gr} applied to the gating electrode. The active region of the QCL, with a peak gain at around 3 THz, is sandwiched between a bottom gold plate and the upper CCG metal grating. The CCG was designed as a second-order grating such that single-mode THz radiation will be emitted vertically through the grating apertures, which is then modulated by the electrically gated graphene. Only the central few rings of the CCG (the orange region in Fig. 1(a)) are connected together with spoke-like metal bridges to allow electrical pumping over a small active region beneath. This restricted the otherwise high current in the QCL to only a few amperes. With the correct CCG design, the optical modes are confined in the pumped area so that the QCL maintains a sufficiently low threshold current for lasing action. On top of the CCG, a SiO_2 layer insulates the QCL electrode from the graphene gate electrode; this is followed by the graphene sheet. Fig. 1(b) and (c) shows optical microscope images of the central part of a fabricated device.

Fig. 1(d) plots the cross-sectional view of the calculated electric field distribution of the CCG QCL. The inset shows the E_z distribution (which is responsible for the THz emission into far field) around the CCG apertures. It is estimated that $|E_z|$ is enhanced by a factor of 12 in the graphene region, which corresponds to an intensity enhancement factor of ~ 140 . The resulting enhanced modulating effect of graphene on the CCG QCL is shown in Fig. 1(e), where the intensity of the lasing peak varies from nearly zero at $V_G = -26$ V to a maximum at $V_G = +40$ V. During measurement, the QCL was biased at 14.8 V in pulsed mode operation at a 20 K heat sink temperature, and the graphene was gated at a series of DC biases V_G . The circles in Fig. 1(f) show the average laser output power as a function of V_G . As a comparison, a control device without the graphene sheet was fabricated, and the output power is plotted as a function of V_G as rectangles in Fig. 1(f), with no obvious modulation being observed. Note that with the presence of the graphene, the output power decreases significantly; the power of the integrated device at $V_G = +40$ V is around a quarter of that from the control device.

Figure 1. (a) 3D schematic illustration of the circular-concentric grating (CCG) THz QCL integrated with a graphene modulator. Only the central several rings of CCG (orange region) are connected together to allow electrically pumping over a small active region. Light is emitted out vertically from the surface and modulated by the electrically gated graphene. (b) Optical microscope images showing the central part of a fabricated device. (c) An enlarged view showing details of the graphene and the QCL electrodes, which are insulated by a 450-nm-thick SiO₂ layer. A wrinkle, resulting from folding of transferred chemical vapor deposition (CVD) graphene, is visible at the lower right corner. (d) Cross-sectional view of the calculated electric field ($|E|$) distribution of the CCG QCL, a white arrow indicates the electrically pumped area. The inset shows a representative cross-sectional view of the $|E_r|$ field distribution, which is responsible for the THz emission into the far field, near a CCG aperture, indicating a great field enhancement in the aperture region. (e) Enhanced modulation of the THz wave by the integrated graphene modulator. The intensity of the lasing peak varies from nearly zero at graphene gate voltage $V_G = -26$ V to a maximum at $V_G = +40$ V. (f) V_G dependence of the output power of the CCG QCL with (circles) and without (rectangles) the graphene. The pumping current of the QCL is 2.80 A.

2.2 Integrated dynamically tunable THz polarizer

Optical waveguide is an essential component for any integrated photonics. In the THz QCL, the metal-metal waveguide which drew inspiration from the transmission line in microwave is a great success, leading to the realization of high-performance THz QCLs. Nonetheless, using it as a passive waveguide would be quite lossy. In addition, as its optical modes are sandwiched by the two metal plates, it is not convenient to have the optical modes interact with other materials placed onto of the waveguide. Alternatively, the conventional dielectric waveguide relying on refractive index confinement can be an option. However, it requires unrealistic thick material growth owing to the long wavelength of THz wave. Previously, surface plasmon (SP) waveguiding on a cylindrical metal wire has been shown to be a promising low-loss THz waveguiding method²⁰. However, a flat metal cannot support SP waves. Later, it was found that artificial metallic structures at a deep-subwavelength scale can mimic the SP behavior of the visible and near-infrared light in the longer wavelength region²¹. The resulting surface wave was thus called “spoof surface plasmon (SSP)”. Lately, we developed an integrated THz dielectric-loaded surface plasmon (DLSP) waveguide, which is much simpler in design and fabrication. As shown in Fig. 2(a) and (b), the DLSP waveguide is simply a GaAs coated metal layer butt coupled to the THz QCL. In real device, the GaAs layer is the QCL active region, this further simplifies the fabrication as it removes the need for additional material growth. Different from the DLSP waveguide in short wavelength, where the propagation mode is a hybridization of the surface plasmon mode and the dielectric waveguide mode, the guiding mode of our DLSP waveguide is merely a surface wave tightly confined at the GaAs-air interface. As very little electric field penetrates into the underneath GaAs layer (Fig. 2(b)), the waveguide is of low loss. The propagation length of the THz wave is plotted in Fig. 2(c) as a function of the GaAs thickness. For our device that will be described below, we chose a GaAs thickness of 5 μm , as a balance between the propagation length and the coupling efficiency of the light from THz QCL to the DLSP waveguide.

Based on the integrated DLSP waveguide, we developed a polarization tunable QCL device. As shown in Fig. 2(d), the device consists of a left tapered QCL, a right tapered QCL, both with an integrated DLSP waveguide, and a half racetrack structure that phase-locks the two QCLs. On top of each DLSP waveguide, we introduced an array of

subwavelength ($21\ \mu\text{m} \times 3\ \mu\text{m} \times 0.4\ \mu\text{m}$ compared to $100\ \mu\text{m}$ wavelength) gold antennas to project the polarization of the scattering light into the orientation of the antenna. The antennas are arranged into a second-order grating with a period of $80\ \mu\text{m}$ so that the constructive interference leads to a collimated beam pointing normal to the surface (Fig. 2(e) and (f)). The antennas of the two QCLs are cross-oriented and shifted by $21\ \mu\text{m}$, around one quarter of the SP wavelength ($85\ \mu\text{m}$), which introduces a $\sim\pi/2$ phase difference in two beams from the left and right antenna arrays. Therefore, the superimposition of the two beams in the far field will result in elliptically polarized light. Moreover, as the power from each QCL can be adjusted independently, the polarization of the combined beam will evolve continuously from linear to circular polarization. Fig. 2(g) and (h) show the experimental results. The collected optical power for these measurements is within the central $5^\circ \times 5^\circ$ region of Fig. 2(f), where the two beams are most well overlapped. Fig. 2(g) shows the result with only the right laser being pumped at $3.67\ \text{A}$, indicating that the radiation is excellently linearly-polarized at the direction parallel to the antenna length. Fig. 2(h) shows the evolution of the polarization state with the variation of the left pumping current while fixing the right pumping current at $3.67\ \text{A}$. For the black curve in Fig. 2(h), $I_{\text{max}}:I_{\text{min}} = 56:44$. According to the definition of the degree of circular polarization (DOCP) in Ref. 16, a DOCP value as high as 99% is obtained. This demonstrates that the device is capable of dynamically changing its polarization state from linear to near-circular.

Figure 2. (a) Schematic geometry of the THz QCL with an integrated dielectric-loaded surface plasmon (DLSP) waveguide. (b) Cross-sectional electric field (amplitude) distribution, showing that the THz radiation is coupled from the QCL into the integrated DLSP waveguide, with a coupling efficiency of 55% for a $5\ \mu\text{m}$ thick GaAs layer ($\lambda_0 = 96\ \mu\text{m}$). (c) Calculated propagation length and coupling efficiency of the THz radiation into the DLSP waveguide as a function of the GaAs thickness. (d) Optical microscope image of a fabricated polarization tunable device. The two sets of antennas are cross oriented and vertically offset by $21\ \mu\text{m}$, corresponding to a $\sim\pi/2$ phase shift. The left and right QCLs are phase-locked by a half racetrack structure to ensure coherent interference of the radiation from the two antenna arrays. The scale bar is $300\ \mu\text{m}$ long. (e) Measured far-field patterns of the device with only the left QCL pumped using an injection current of $I_{\text{left}} = 3.49\ \text{A}$. (f) Measured far-field patterns with all three parts of the structure (left, right QCLs and the half racetrack) electrically pumped, the injection currents are $I_{\text{left}} = 3.49\ \text{A}$, $I_{\text{right}} = 3.67\ \text{A}$ and $I_{\text{RT}} = 0.53\ \text{A}$. (g) Measured polarization state of the right arm. (h) The evolution of the polarization states when changing the injection current to the right QCL, and keeping that to the left QCL at $3.67\ \text{A}$.

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