Terahertz quantum cascade lasing in disordered photonic systems

Abstract

Scattering, which is created by dust, clouds, white paints or imperfections of artificial material such as photonic crystal, is normally undesirable in the field of photonics. Unequivocally, a deep understanding of disorder can help to overcome the issues arising from scattering. However, it is also possible to utilize the disorder to create useful photonic devices. A most acknowledged example is that of random laser, in which lasing action is sustained by multiply scattering of light within the disordered media. Disordered structures are also proposed for the applications including wavelength filters, optical switches, sensors and cavity quantum electrodynamics. Most of the research work on disorder has been focused on short wavelength range. Several years ago, the tide spread to mid-infrared range with the experimental demonstration and theoretical optimization of mid-infrared random laser at ~10 μm. However, in the technically important terahertz (THz) frequency range, the disordered photonics are least explored. So this thesis investigates disordered systems based on the double-metal waveguide of THz quantum cascade lasers and explores the emission properties with the aid of gain.

As the first demonstration, we design and fabricate one-dimensional disordered grating structures on top of the double-metal waveguide of the THz quantum cascade laser. The disorder is introduced into the waveguide by dislocating the position of each aperture from a periodic configuration. Numerical calculation indicates that the introduced disorder creates multiple microcavities with small optical losses at the bandgap frequency window of the underlying long-range orderness. With electrical pumping, 8 emission peaks around 3.2 THz are observed, which are located inside the bandgap region of the periodic counterparts. Experimental measurements and simulation work provide strong evidence for spatial localizations of light.

Instead of utilizing long-range orderness for creating microcavities, we also investigate two-dimensional disordered structures consisting of randomly-distributed pillars fabricated from a quantum cascade gain medium, in which long-range ordereness does not exist. Due to the strong scattering efficiency of a high-index dielectric pillar for transverse-magnetic polarized (TM) wave, we show that such structures can achieve multi-mode lasing, with strongly localized modes at THz frequencies. This is a typical feature of random lasers. The weak short-range order induced by the pillar distribution is sufficient to ensure high quality-factor modes that have a large overlap with the active material. It is also found that the emission spectrum can be easily tuned by tailoring the scatterer size and filling fraction.

While the pillar scatterer is beneficial for better performance of multimode lasing (lower threshold, more lasing modes etc.) due to high scattering efficiency, it also limits the lasing to the Mie resonance frequency range, impeding the broadband random application. The non-resonant scatterers feature a relatively frequency-insensitive scattering efficiency, although the scattering efficiency is normally weaker than that of the resonant type. Therefore, we further develop metallic pillars, a class of non-resonant scatterers with high scattering efficiency in THz frequency range. Such metallic scatterers are especially suitable for transverse-magnetic (TM) polarized light. In absence of the plasmonic resonance of the metallic pillar for TM mode, high scattering efficiency and small ohmic losses can be maintained over a broad bandwidth, making possible a broadband random laser constructed by these metallic pillars. We demonstrate that such random lasers, with metallic pillars embedded in THz quantum cascade laser gain medium, outperform their dielectric-scatter counterparts in terms of lasing spectral range, the number of lasing mode and laser threshold. Complex emission spectra are captured and more than 25 emission peaks can be observed across the gain spectral range of the laser.