Metal-Metal Terahertz Quantum Cascade Laser with Hybrid Mode Section

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Abstract— **A hybrid mode section is integrated into the end of the metal-metal (MM) waveguide of a terahertz (THz) frequency quantum cascade laser (QCL) by removing sub-wavelength portions of the top metal layer. This allows a hybrid mode to penetrate into the air, which reduces the effective index of the mode and improves the out-coupling performance at the facet. The transmission of the processed metal-metal hybrid section (MMHS) waveguide is further increased by ensuring its length fulfills the criterion for constructive interference. These simple modifications to a 2.5 THz MM QCL waveguide result in a significant increase in the output emission power. In addition, simulations show that further improvements in out-coupling efficiency can be achieved for lower frequencies with effective refractive indices close to the geometric mean of the indices of the MM waveguide and air.**

I. INTRODUCTION

THz QCLs attain the highest temperature performance in MM waveguides, in which the laser mode is completely confined in the active region by two metal layers. However, the mode dimension in the growth direction is less than the wavelength. As a consequence, both a significant impedance mismatch at the laser facet and strong diffraction limit the out-coupling efficiency. Therefore several strategies have been employed to improve the out-coupling efficiency such as fabricating gratings for low divergence emission [1] and tapered horn antennas [2]. Recently, a hybrid waveguide [3] was formed by allowing the mode of a metal-metal waveguide to leak through a thin metal layer into a low index polymer. In this work, the out-coupling performance of a MM QCL is improved by reducing the effective refractive index at the facet via removing portions of the top metal layer.

II. RESULTS

A schematic diagram of the MMHS waveguide and the used experimental arrangement are presented in Fig. 1. The hybrid section length is only 2.5% of the total waveguide which conserves the high confinement factor of the MM waveguide along the majority of the QCL. A significant improvement in the out-coupling efficiency is demonstrated from measurements on a QCL which is presented in Fig. 2. A MM waveguide is compared to the MMHS waveguide with respect to both total out-coupling performance and spectral emission. For a current density of 720 A/cm^2 the total power is increased by a factor of approximately 3 (Fig. 2(a)). The spectral emission at 2.5 THz is pronounced, since the hybrid section length l is optimized for constructive interference according to $l=mc/(2fn_{eff})$ (Fig. 2(b)).

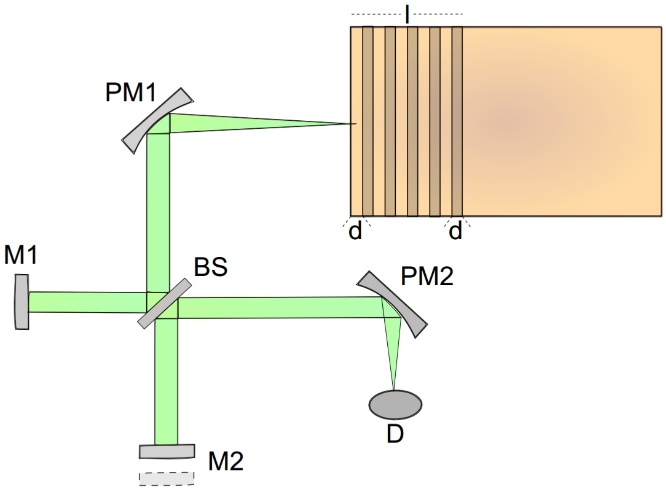

Fig.1: Schematic diagram of the experimental arrangement, showing relevant dimensions of the metal-metal hybrid section (MMHS) waveguide. The length of the hybrid section l is 38 µm. The distance between the metal lines d is 1 µm. A Michelson interferometer is used to detect the spectrum with a pyro-electric detector D.

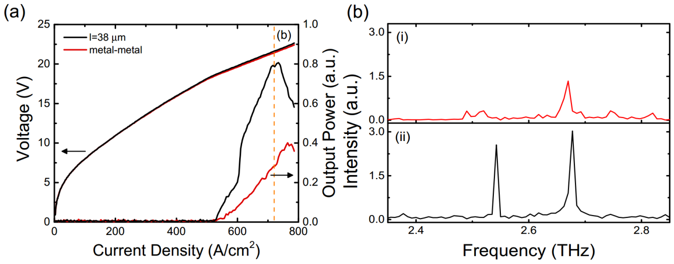

Fig.2: (a) QCL output power and voltage as a function of current density for both the MMHS waveguide (black) with l=38 µm and the MM waveguide (red). The spectra from the MM (i - red) and MMHS (ii - black) QCL waveguides are shown for a current density of (b) 720 A/cm^2. The MMHS waveguide QCL shows a pronounced emission at approximately 2.5 THz.

Here m is an integer, c the speed of light, f the frequency and n_{eff} the effective refractive index of the mode.

In order to investigate the out-coupling process in more detail and explore the full potential of the proposed concept, finite difference time domain (FDTD) simulations from a commercial software package were used. The constructive interference in the hybrid section is illustrated in Fig. 3 by

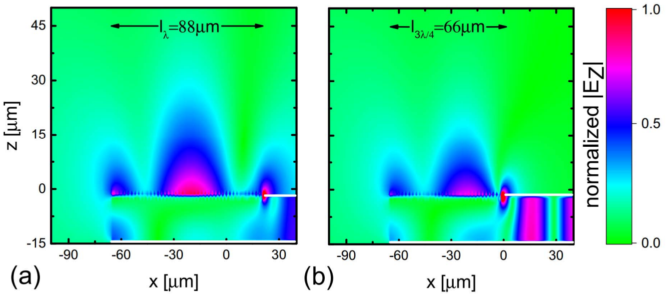

Fig.3: Distribution of $|E_z|$ at a frequency of 1.7 THz for (a) constructive and (b) destructive interference. Both MMHS waveguides differ only in the length of the hybrid section which is 88 µm in (a) and 66 µm in (b).

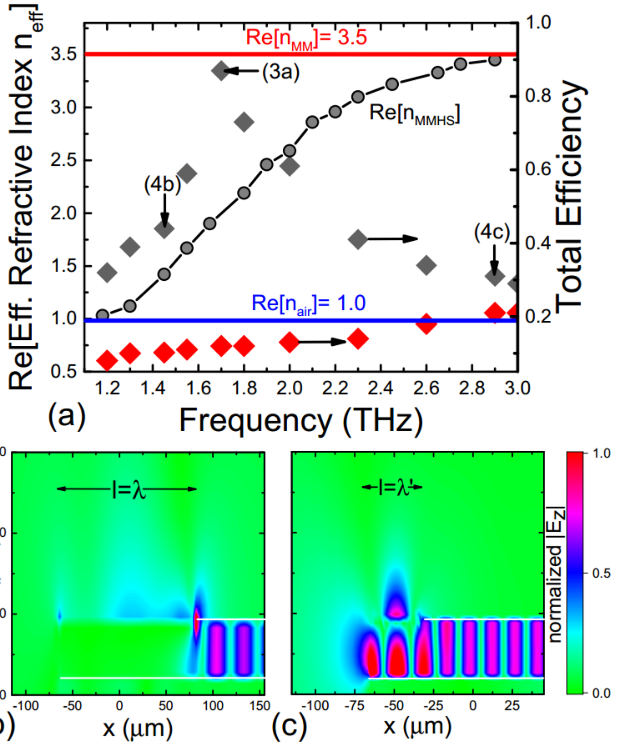

Fig.4: (a) Frequency dependent total efficiency and n_{eff} for MM and MMHS waveguides. The peak in total efficiency at 1.7 THz is obtained by choosing n_{eff} close to the geometric mean of the indices of the MM waveguide and air. The mode distribution of $|E_z|$ for (b) 1.45 THz and (c) 2.9 THz shows strong reflections at the corresponding interfaces.

plotting $|E_z|$ for two hybrid sections whose satisfy the condition for constructive and destructive interference. In both cases the 1/e penetration depth of the mode into the air is the same. However the amplitude at the air-interface is much greater for constructive interference (Fig. 3(a)) than for destructive interference (Fig. 3(b)).

The effective refractive index n_{eff} of the hybrid mode is investigated as a function of frequency in Fig. 4(a) (grey circles). The effective waveguide index can be defined as $n_{eff}=\beta c/\omega$, where ω is the angular frequency, c is the speed of light in vacuum and β is the propagation constant of the mode. In Fig. 4(a) it becomes clear that n_{eff} decreases with decreasing frequency. For instance, at a frequency of 2.5 THz n_{eff} is slightly reduced with respect to the MM waveguide (3.1 vs 3.5). In addition to n_{eff} the total efficiency (defined as the total radiated power over the input power) is also shown as a function of frequency in Fig 4(a) (grey diamonds). The total efficiency is maximized for a frequency of 1.7 THz.

Interestingly, an optimum point of operation close to the geometric mean of the indices of the MM waveguide and air is observed. For this specific point of minimized reflections at both interfaces about 87 percent total efficiency are achieved at a frequency of 1.7 THz. Comparing this value to the MM waveguide (12 percent total efficiency, red diamonds) an improvement factor of about 7.25 is predicted (Fig. 4(a)).

For low n_{eff} the reflection at the hybrid – air interface is significantly reduced, whereas the reflection at the MM – hybrid interface is still decent (Fig. 4(b)). In contrast, at higher indices the reflections are high for the air – hybrid and low for the MM – hybrid interface (Fig. 4(d)). The decrease in n_{eff} is also accompanied by an increase of the penetration depth l_{eff} according to $l_{eff}^2 = \lambda^2 /(4\pi^2(n_{eff}^2-1))$. The increase in the spatial extent of the mode decreases the spatial mismatch between the waveguide mode and the air modes at the hybrid –air interface which reduces its reflection coefficient.

III. CONCLUSION

In conclusion, by removing sub-wavelength portions of the top layer of a MM waveguide a hybrid section has been formed, where the lasing mode can penetrate into air. The hybrid section is found to improve significantly the out-coupling efficiency of the MM waveguide, and in contrast to other schemes, the approach presented here is straightforward to implement. In addition, FDTD simulations show that an almost ideal out-coupling performance of about 87 percent can be achieved, if a balanced reflection minimization is employed.

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