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Short Communication

Light gain amplification in microcavity organic semiconductor laser diodes under electrical pumping

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Organic semiconductor is one of the most promising luminescent and lasing materials that can be chemically synthesized with a controllable performance and possess high cross-section of stimulated emission [1]. Organic semiconductor laser diodes (OSLDs) can be prepared by simple processing technologies and integrated easily with other optoelectronic devices. As a result, OSLDs would have appealing applications in low cost, compact, flexible and tunable lasers with spectral region from ultraviolet to near infrared [2–4]. Although lasing has been widely demonstrated under optical pumping, electrically pumped OSLDs are rather difficult to realize because the expected high threshold current is hard to reach in low electrical conductivity organic semiconductors and electroluminescence (EL) efficiency is much decreased under high current [5].

As a wavelength-scale Fabry-Perot resonator, planar microcavity is a practical structure for lasers that can effectively modify spontaneous and stimulated emission properties of materials inside according to the Purcell effect and Fermi gold rule [6]. Microcavities with high quality factor (Q) can result in low threshold and reduce the difficulty of achieving electrically pumped lasing in OSLDs. The first reported electrically pumped microcavity OSLD shows clear threshold behaviors in output light intensity and full width at half maximum (FWHM), reasonable spatial coherence, obvious cavity mode characteristic, and in particular, low threshold current density (J_{th}) [7]. Because the reported J_{th} is far below the expectation level, questions are raised as that the observed threshold phenomena are induced by optical gain under stimulated emission mechanism or some special optical phenomena under spontaneous emission mechanism [8].

Herein, based on high-Q microcavity OSLD, we present an electrically pumped vertical-cavity organic semiconductor optical amplifier and its light gain amplification phenomenon. Moreover, we demonstrate that electrically pumped quasi-continuous-wave (QCW) lasing can be obtained with a much lower J_{th} of the level at mA/cm^2, indicating that the realization of continuous-wave (CW) OSLDs and their wonderful prospects for practical application can be expected in the near future.

As shown in Fig. 1a, OSLDs are based on a half-wave microcavity, and have the similar detailed structure as reported previously [7]. The measured reflectance spectrum of the microcavity OSLD shows a cavity mode at around 622 nm (Fig. S1 online), which is close to the photoluminescence (PL) peak of the Alq:DCJTI active layer (Fig. S2 online). The optically pumped lasing characteristics of the OSLD sample were examined under QCW excitation from a 405 nm laser diode (LD). Fig. 1b shows output emission spectra and peak emission intensity under different light excitation intensity, indicating a clear optically pumped threshold (P_{th}) around 20 mW/cm^2, after which output emission grows rapidly due to light amplification. Spectra peak locates at the cavity mode position of 621.7 nm, and the FWHM is narrowed from 1.64 nm below P_{th} to 0.856 nm above P_{th}. The measured P_{th} have not considered the following factors, such as the transmittance and absorption of cavity mirror at 405 nm, the difference in thickness and absorption coefficient between the active layer and other organic layers, the length difference of exciton recombination region between optical pumping and electrical pumping. Therefore, the actual P_{th} should be more than dozen times smaller.

The lasing characteristics were further examined under QCW electrical pumping. Fig. 1c show output-input properties of the sample in both log-log and L-L scales. The dependence of output emission intensity on input current density indicates a J_{th} at about 1.8 mA/cm^2, above which emission spectra show a sharply increase of output intensity due to light amplification and the consequent narrowing from 1.38 nm below J_{th} to 0.835 nm above J_{th}. The Q value of the microcavity is about 450. Fig. 1d shows that the electrically pumped OSLD has lasing emission peak at 621.7 nm, the same position as in the optical pumping case. As shown in Fig. S3 (online), the consistent emission peak indicates that the optical constant and thickness of each organic layer remain unchanged with the increase of current density, and also suggests that output characteristics of organic lasers are more likely to be temperature-

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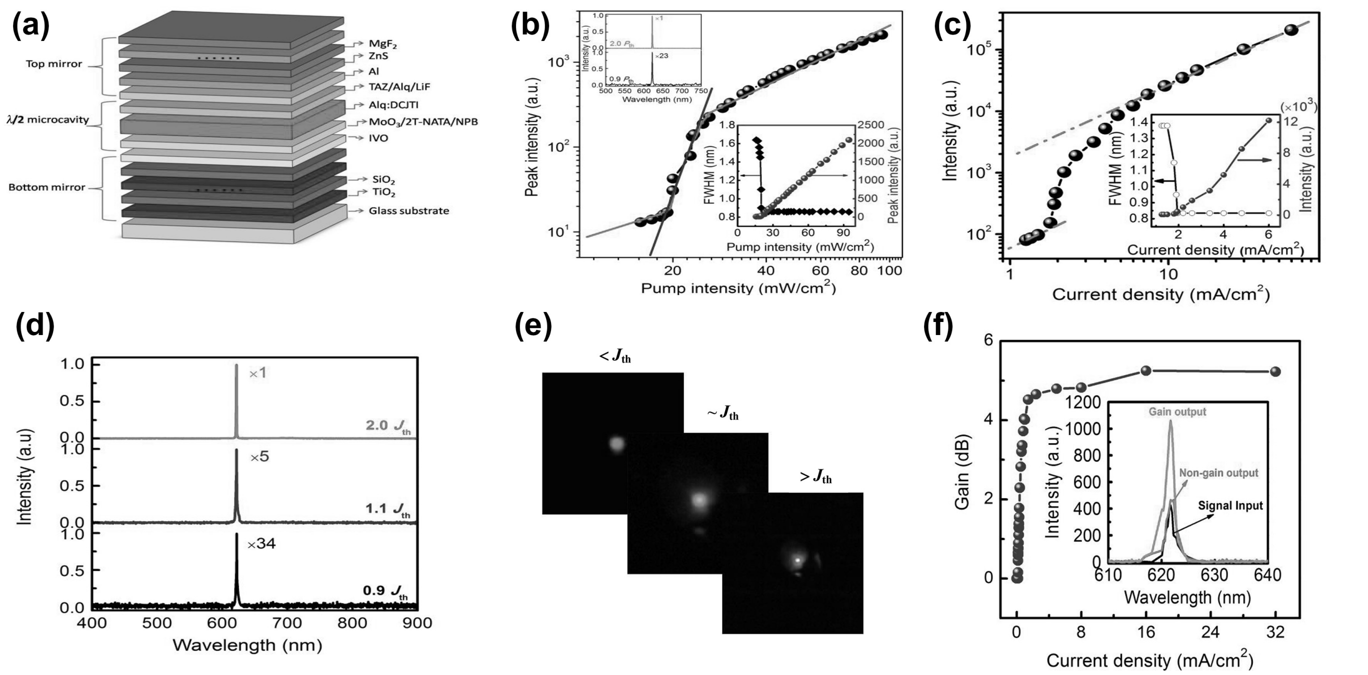

Fig. 1. (Color online) Lasing performance of microcavity OSLD. (a) Device structure. (b) Dependence of output spectrum peak intensity (P_{out}) on pump intensity (P_{in}) (log-log curve), the red and blue lines are guides for the eye. The left inset shows output emission spectra at different P_{in}. P_{th} represents optically pumped threshold. Times sign means that the spectrum intensity has been enhanced by multiples of the number for making a clear comparison. The right inset shows P_{out} and FWHM as a function of P_{in} (L-L curve). (c) Dependence of output spectrum peak intensity on current density (log-log curve), the red dashed lines are guides for the eye. The inset shows output spectrum peak intensity and FWHM of the device as a function of injection current density (L-L curve). (d) Output emission spectra at different current density. (e) Far field spot patterns at different current density. (f) Dependence of light gain amplification in microcavity OSLD on injected current density under the constant LD pumping intensity of 0.028 mW/cm^2 at 405 nm. The inset shows the spectra of input signal light, the device output without input signal (non-gain output) and with input signal (gain output) at the current density of 0.38 mA/cm^2.

insensitive. Micro-region PL spectra show that the sample has a nonuniform distribution of cavity length due to non-optimized vacuum thermal evaporation process (Fig. S4 online). Consequently, the minimum FWHM is restricted and cannot be narrowed down continuously above J_{th} (inset of Fig. 1c).

Fig. 1e illustrated far field spot properties of the sample under different current density. The spot pattern of the microcavity OSLD shows a uniform intensity distribution below J_{th}, a center-enhanced distribution near J_{th}, and an obvious Gauss distribution above J_{th}, which is in accord with the typical laser characteristic. The electrically pumped light gain amplification was further examined by using a microcavity OSLD as Fabry-Perot amplifier (Fig. S5 online). Because of the lack of appropriate signal light source, we employ 405 nm-excited sample PL as the input signal light. The excitation intensity of 405 nm LD is 0.028 mW/cm^2 and remains unchanged during the measurement. The intensity of signal light is much lower than P_{th} to ensure that signal light have negligible effect on gain amplification caused by electrical pumping. Gradually increased gain of the microcavity amplifier with injected current density is obtained until it reaches around J_{th}, above which the gain tends to be saturated. As shown in Fig. 1f, the maximum gain is 5.25 dB at 16 mA/cm^2, and the gain is 2.2 dB at 0.38 mA/cm^2. The observed light gain follows the basic rules of vertical-cavity semiconductor optical amplifiers (VCSOAs).

High-Q microcavity limits cavity mode numbers and permits only confined transitions between energy levels, which may change excited state loss process in OSLDs. At the allowed cavity modes, greatly increased photon density and internal quantum efficiency of devices lead to increased probability of stimulated emission in four-level organic materials, and consequently facilitate population inversion in OSLDs with a low current density. The mechanism behind deserves further investigation.

In summary, we have demonstrated electrically pumped quasi-continuous-wave lasing can be realized in microcavity OSLDs in a very low current density. Moreover, an electrically pumped vertical-cavity organic semiconductor optical amplifier has been realized with a maximum optical gain of 5.25 dB.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.scib.2017.12.010.

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