META 2023, PARIS - FRANCE, JULY 18 – 21, 2023

Integrated Q-switched lasing element in the NIR with transition metal dichalcogenide gain and graphene saturable absorption

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Abstract: We propose and analyze an integrated passively Q-switched lasing element in the NIR based on a nanophotonic disk resonator and enhanced with the contemporary MoS_2/WSe_2 TMD hetero-bilayer and graphene monolayer to provide the optically-pumped gain and saturable absorption, respectively. The configuration is rigorously evaluated utilizing a temporal coupled-mode theory framework. Following a meticulous design process, the pulsed lasing source delivers mW peak power and ps duration pulses, with a repetition rate of tens of GHz for sub-mW pump power.

The development of highly efficient, monolithically integrated light sources in the technologically mature silicon-on-insulator (SOI) platform constitutes a key scientific and technological goal for future high-density integration photonic circuitry. A new avenue towards this goal has been opened by the exploitation of the novel luminescence and nonlinear properties of two-dimensional (2D) materials, such as the semiconducting transition metal dichalcogenides (TMDs) and the semi-metallic graphene [1]. In this work, we propose and computationally examine an integrated passively Q-switched lasing component in the near-infrared (NIR), based on a nanophotonic disk resonator where both the gain and the saturable absorption (SA) mechanisms are provided by 2D materials. The contemporary MoS_2/WSe_2 TMD hetero-bilayer is selected as the gain medium; it emits light at 1128 nm (1.1 eV) after being optically pumped at 740 nm (1.675 eV). To enhance the efficiency of the light source, the gain medium is pumped by appropriately exciting a whispering-gallery mode of the cavity near the pump wavelength using guided light. A graphene monolayer is additionally utilized to harness the required ultrafast and low-saturation-intensity SA effect. To numerically analyze and design the proposed light source, we rigorously develop a temporal coupled-mode theory (CMT) framework [2, 3], fed by linear finite element method (FEM) simulations. The lasing and pumping transitions of the three-level gain medium (MoS_2/WSe_2 heterostructure), are described by induced electric polarization fields which are incorporated in the CMT framework employing first order perturbation theory. The polarization fields follow equations of homogeneously broadened Lorentzian oscillators and the carrier dynamics are described by appropriate semiclassical rate equations. The latter are introduced in the CMT framework using only the standard slowly-varying envelope (SVEA) and rotating-wave (RWA) approximations. Overall, the developed CMT framework is capable of accurately evaluating the fundamental lasing characteristics, including the lasing frequency and the dynamic response, and allows to extract useful practical design guidelines as well as conduct a linear stability analysis to identify operation regimes of the pulsed lasing structure.

The proposed Q-switched lasing configuration is depicted in Figure 1(a) and consists of a silicon-rich nitride (SRN) disk resonator on silica substrate. A double bus waveguide scheme is employed to efficiently excite the pumping mode and extract the emitted light from the lasing mode. The MoS_2/WSe_2 bilayer and graphene monolayer are patterned in disks matching the resonator and placed on top of it, separated by a 60-nm layer of hexagonal boron nitride (h-BN). The geometric parameters of the structure are marked in Figure 1(b). The heights of the disk resonator and the h-BN layer have been judiciously selected, in order to allow for the lasing mode to interact strongly with both the TMD bilayer and graphene monolayer, which is a key prerequisite for the lasing element to operate in the pulsed regime. Concurrently, the employed configuration enables the pumping mode to interact strongly only with the TMD bilayer, hence, leaving unaffected the nonlinear response of graphene. This is schematically illustrated in Figure 1(c, d), where the norm of the tangential to the 2D materials electric field is depicted in the $x-y$ plane for the two modes. Due to the highly efficient pumping scheme and the strong light-matter interaction between the 2D gain medium and the lasing mode, the lasing threshold is only $26\ \mu\text{W}$. In Figure 1(e) we depict the output peak power, the full-width half maximum (FWHM), and the repetition rate of the obtained Q-switched pulses as a function of the pump power. By increasing the pump power, the pulse width decreases, while the peak power and the repetition rate increase. The proposed Q-switched lasing element is capable of delivering pulsed light inside an integrated bus waveguide with mW peak power, ps duration and GHz repetition rate even for sub-mW pump power, rendering it promising for optical communication and sensing applications in the NIR. An individual Q-switched pulse for $P_p = 0.5$ mW is depicted in the inset of Figure 1(e), which has an asymmetric lineshape with slightly longer leading edge.

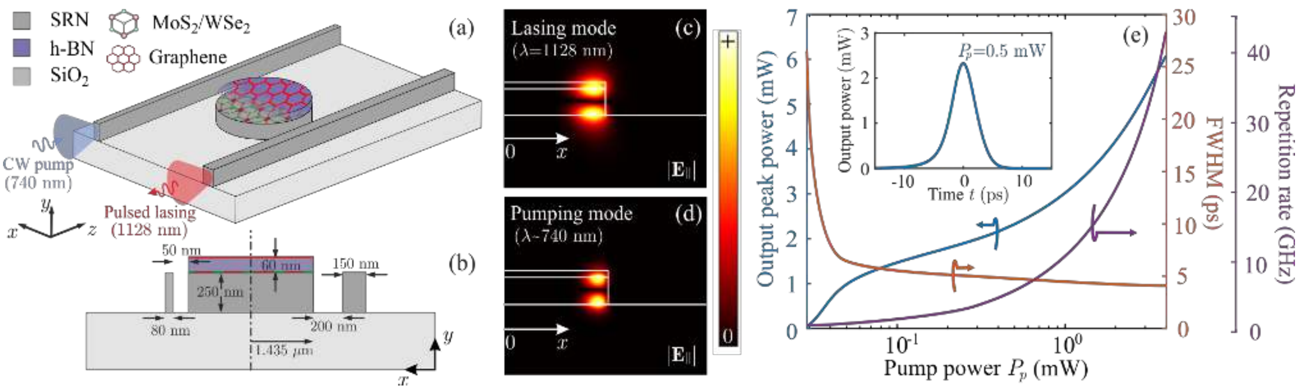

Figure 1. (a) Schematic of the proposed Q-switched lasing element consisting of a disk resonator comprising a MoS_2/WSe_2 TMD hetero-bilayer (gain) and a graphene monolayer (SA). The cavity is side-coupled to two dissimilar bus waveguides. (b) xy-plane cut of the structure with the geometric parameters. (c, d) Norm of the tangential to the 2D materials electric field for the (c) lasing and (d) pumping mode. (e) Output peak power, FWHM and repetition rate of the Q-switched pulses as a function of the pump power P_p. Inset: Individual Q-switched pulse for $P_p = 0.5$ mW.

Acknowledgements

This work was supported by the Hellenic Foundation for Research and Innovation, Project Number HFRI-FM17-2086.

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