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

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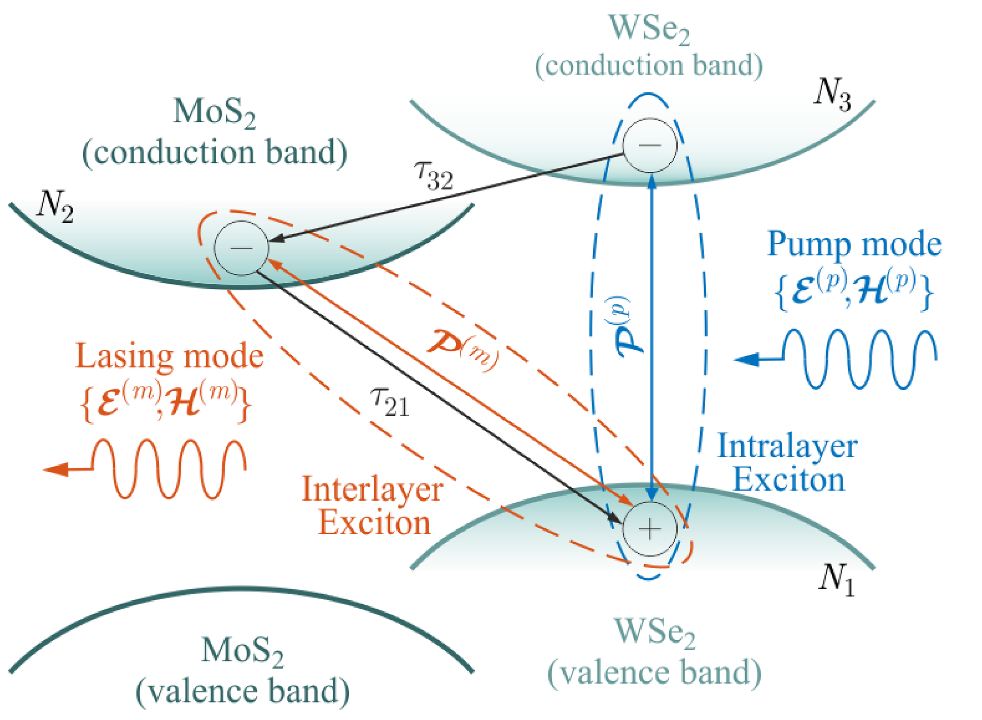
I. Introduction

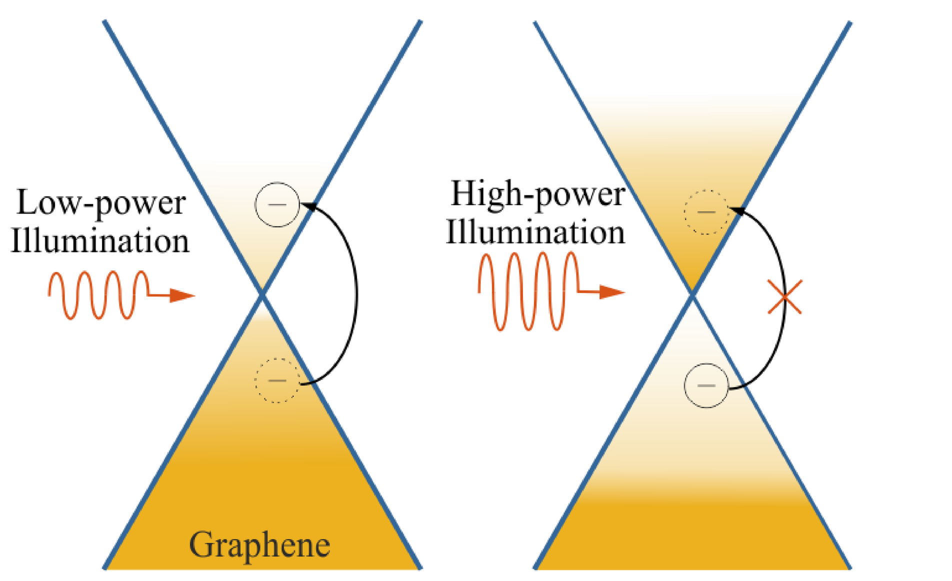
- **Motivation**:
  - Bring **passive Q-switching** at the **nanoscale** aiming to develop efficient integrated **silicon-on-insulator (SOI)-**compatible **pulsed laser sources** in the near infrared (NIR).
  - Exploit the novel luminescence, linear and nonlinear properties of contemporary **two-dimensional (2D) materials** to provide *both* the **gain** and **saturable absorption (SA)** mechanisms.
- **Objective**:
  - Propose, design, and numerically analyze an integrated **nanophotonic passively Q-switched** lasing element based on a **silicon-rich nitride (SRN) disk resonator**, enhanced with gain provided by a **MoS_2/WSe_2** transition metal dichalcogenide (TMD) **hetero-bilayer** and SA by a **graphene monolayer**.

II. Computational framework

- Accurate and efficient **temporal coupled-mode theory (CMT) framework**, rigorously extracted from the Maxwell-Bloch equations using **first-order perturbation theory** and utilizing the standard **slowly-varying envelope** and **rotating-wave** approximations [1].
  - Capable of treating both **sheet** and **bulk gain media**.
  - Capable of incorporating nonlinear effects including SA in 2D materials [2].



- MoS_2/WSe_2 is a three-level 2D gain medium with **long radiative recombination times** (~ns).
- Emits light at 1128 nm due to radiative recombination of **interlayer excitons** after being optically pumped at ~740 nm [3].
- **Pumping with guided light** to increase absorption efficiency and **lower lasing threshold**.
- The lasing and pump transitions are described by **induced electric polarization fields** following the damped Lorentzian oscillator equations and the carrier dynamics by **semiclassical carrier-rate equations**.



- Graphene possesses **ultrafast** and **low saturation intensity** (~1 MW/cm²) **SA effect**, attributed to Pauli blocking of interband transition [4].
- Instantaneous graphene SA model where only losses are quenched by the lasing mode:

$$\sigma_{\mathrm{gr}} = \frac{\sigma_0}{1+|\mathbf{E}^{(m)}|^2/E_{\mathrm{sat}}^2}$$

- **Overall**, the developed CMT framework consists of **seven coupled first-order nonlinear ordinary differential equations** [two equations for cavity amplitudes (lasing and pump), two equations for induced polarization (lasing and pump), and three carrier rate equations].
  - The coefficients of the CMT equations are evaluated through linear electromagnetic **finite element method (FEM)** simulations.

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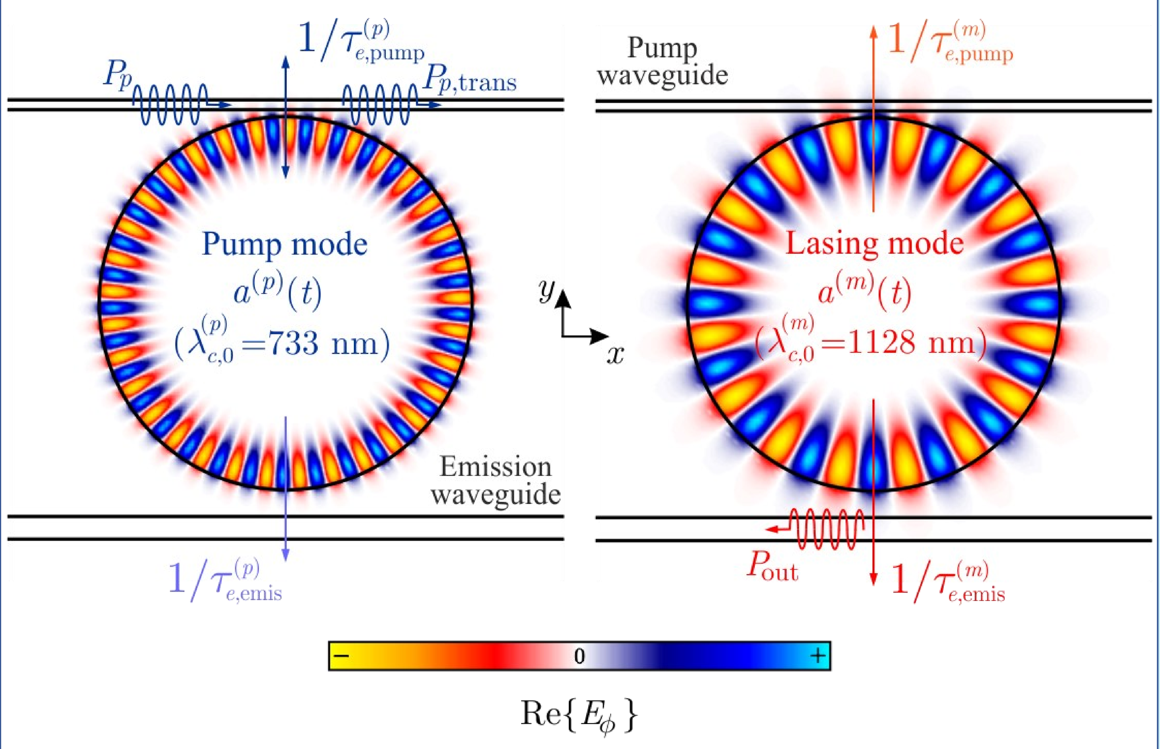
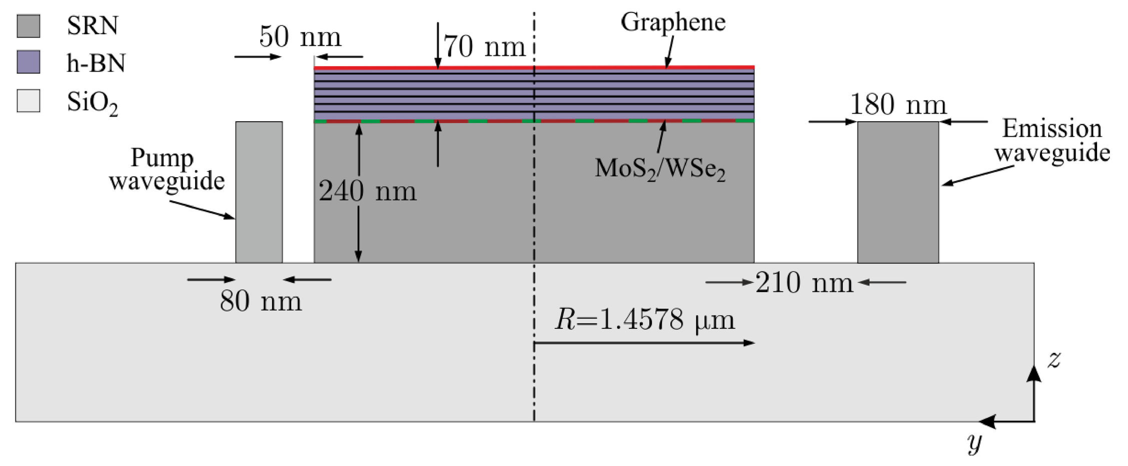
III. Integrated laser structure

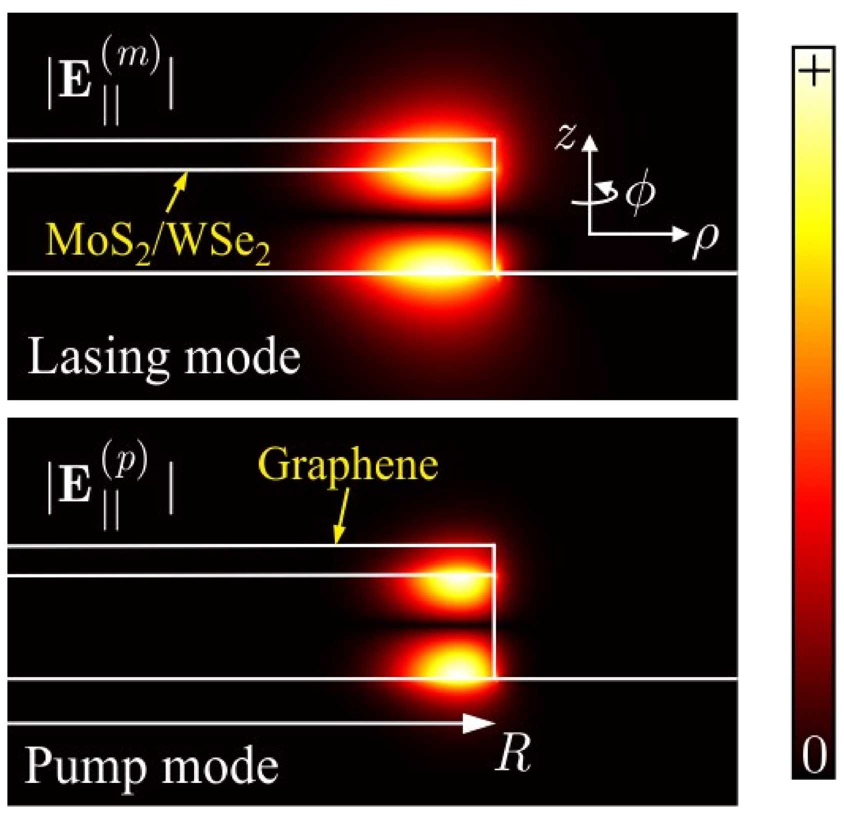


- SRN disk resonator on SiO_2 substrate supporting tightly-confined **WGMs** with **high Q-factors**.
  - SRN is **transparent** at *both* the lasing and pump wavelengths.
- MoS_2/WSe_2 and graphene are patterned in disks matching the resonator and placed on top of it, separated by a spacer of (multilayer) **hexagonal boron nitride (h-BN)**.
  - h-BN allows for tailoring the **modal overlap** with the 2D gain and SA media.
- To efficiently excite the pump mode and extract the emitted light from the lasing mode, the resonator is side-coupled to **two dissimilar bus waveguides**.
  - Each mode is predominately coupled only to one waveguide.



IV. Cavity design

- The heights of the SRN and h-BN layers in the disk resonator are designed to achieve:
  1. **Strong** light-matter interaction between the **lasing mode** and both **MoS_2/WSe_2** and **graphene**.
  2. **Strong** light-matter interaction between the **pump mode** and **MoS_2/WSe_2**.
  3. **Weak** light-matter interaction between the **pump mode** and **graphene**.
- For the coupled cavity, we opt for:
  1. **Over-critical coupling** condition between the **lasing mode** and the emission waveguide to increase the output emitted power.
  2. **Critical coupling** condition between the **pump mode** and the pump waveguide to maximize absorption efficiency (η_p = 1), minimizing the lasing threshold.



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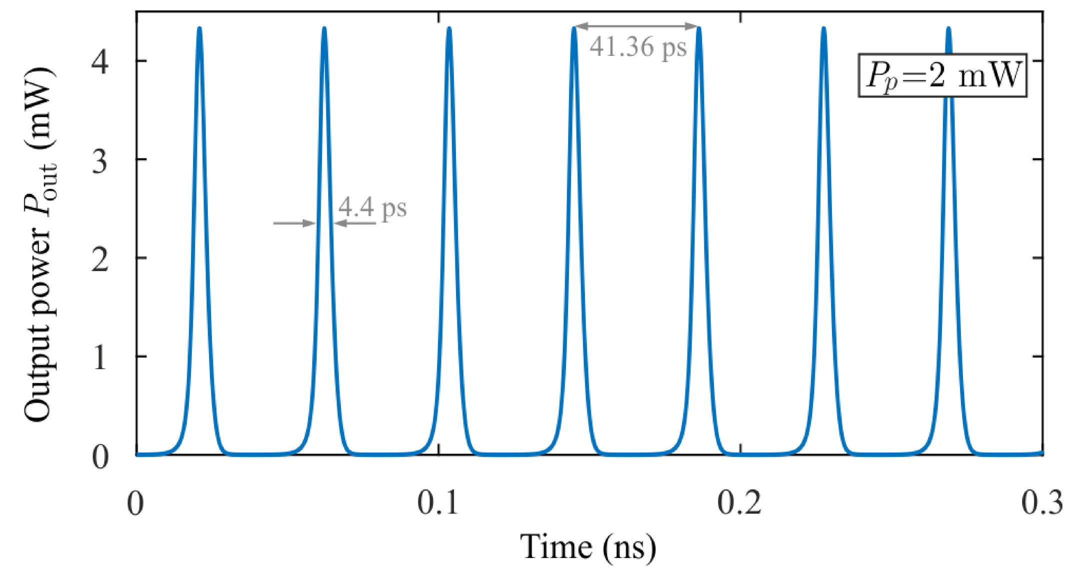
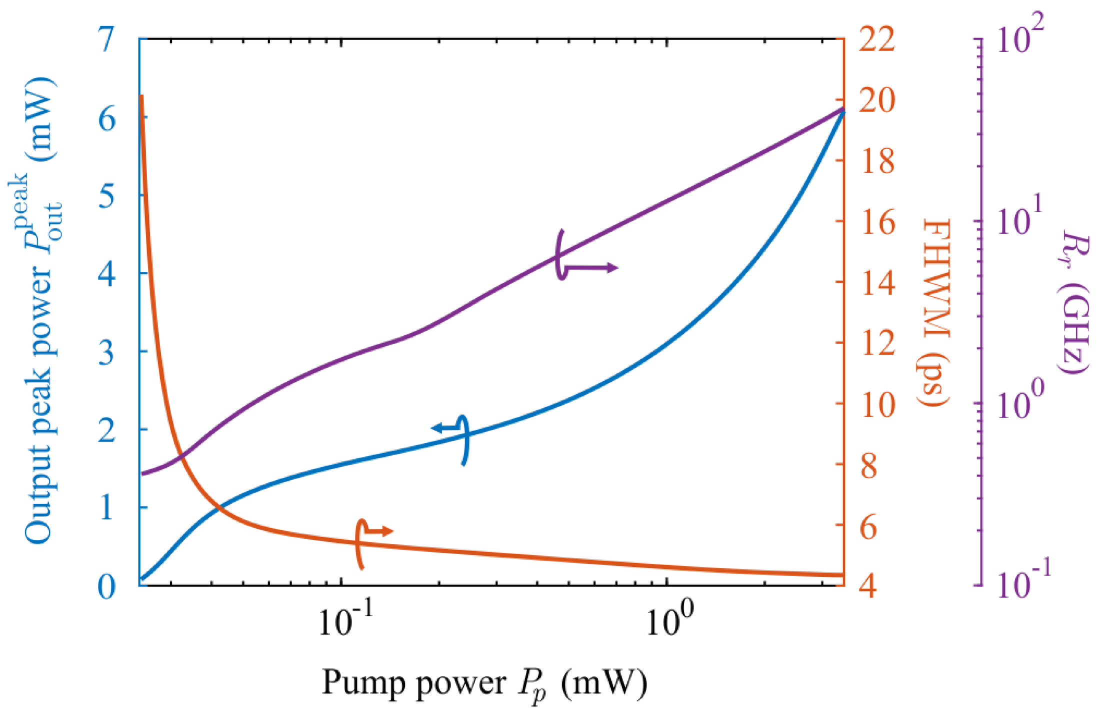
V. Laser pulsed operation

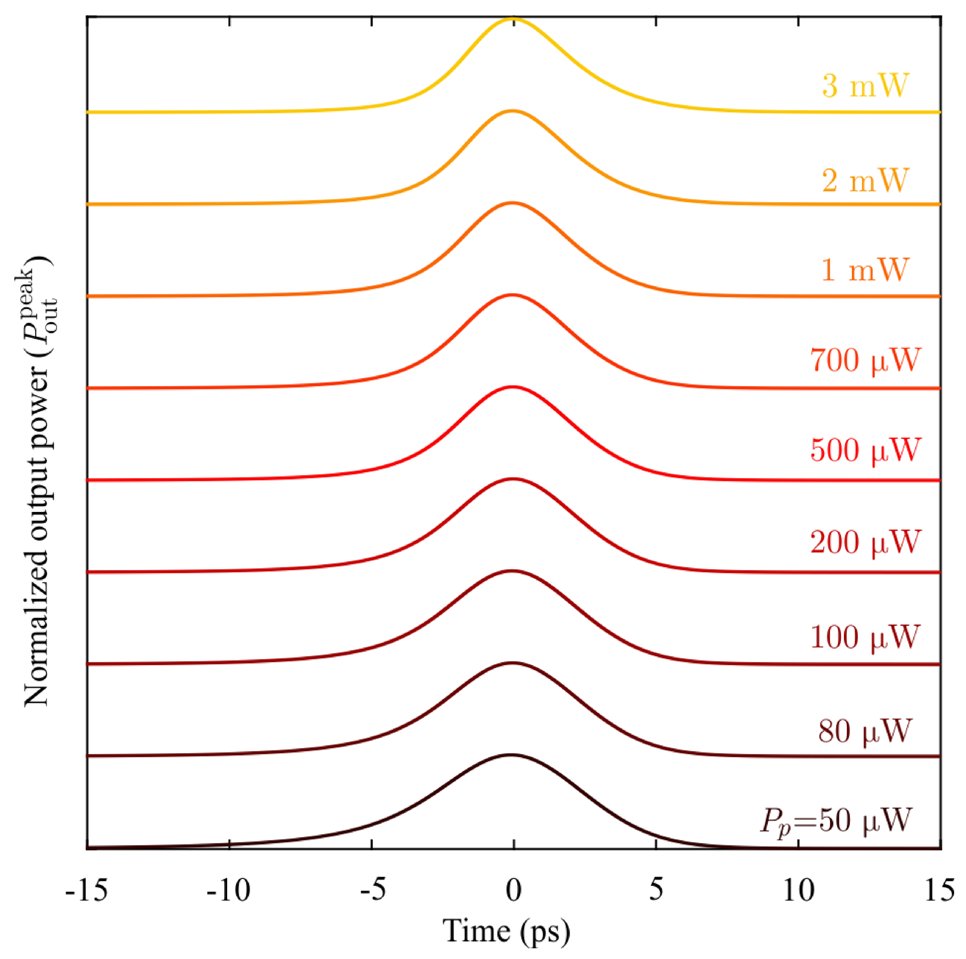
- Due to the fulfillment of the **critical coupling condition** for the pump mode, **the CW lasing threshold** is just **25 μW**.
- **Q-switched operation** with infinite extinction ratio is obtained from pump power levels just above the lasing threshold **up to 3.5 mW**.



- The output **peak power** of the Q-switched pulses increases with the pump power from 79 μW to 6.1 mW. **1 mW peak power** is achieved for just **P_p = 45 μW**.
- **FWHM** is in the **ps timescale** and decreases slowly from 6.35 ps (P_p = 45 μW) to its lowest value of 4.35 ps (P_p = 3.5 mW).
- **Repetition rate** R_r increases in a practically **linear manner** with pump power and in a range of two orders of magnitude spanning **from 0.41 GHz** (2.4 ns) **to 41.7 GHz** (24 ps).



- The **lineshape** of the individual Q-switched pulses is **highly-symmetric** as saturable and non-saturable losses of the lasing mode are equally dominant.
- Transition from pulses with slightly longer leading edges to pulses with longer trailing edges as the pump power increases, revealing the **non-negligible** role of the pump mode in the overall lasing dynamics.



VI. Conclusions

We have **proposed** and thoroughly **studied** a **nanophotonic passively Q-switched lasing element** based on a WGM disk cavity enhanced with **MoS_2/WSe_2** optically-pumped gain and **graphene** SA. The response of the lasing structure has been accurately **evaluated** through a rigorous **CMT framework**. Overall, the proposed laser has an ultralow lasing threshold and emits pulsed light of mW peak power, ps duration and GHz repetition rate, even for sub-mW pump power levels, rendering it **highly promising** for a variety of **optical communication** and **sensing applications** in the NIR.

VII. References

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