University at Buffalo *The State University of New York* | REACHING OTHERS

Putting the Spin in Lasers

Sean R.B. Bearden, Jeongsu Lee, Evan Wasner, Igor Zutic

State University of New York at Buffalo

INTRODUCTION

A lasers is designed to generate coherent light based on quantum mechanical properties that have theoretical foundations tracing back to Albert Einstein [1]. Despite being a device born out of the era of quantum mechanics, the laser as most of us know it today does not utilize other quantum mechanical properties accessible to its operation.

Physicists and engineers have revised the conventional laser, creating a design that introduces concepts from spintronics to laser operation. Our research focuses on exploiting the spin and charge degrees of freedom (spintronics) in our theoretical laser model. This type of laser is known as a spin laser, that is, a laser that manipulates the intrinsic spin properties of carriers (electrons and holes). It is rather simplistic in its contribution to the conventional laser's theoretical foundation, yet full of surprising and unintuitive results.

Before interpreting our results, we first compare the operation of a conventional laser and a spin laser. Next, we will review experimental observations, which serve as motivation for our research. Continuing, we will look at static operation of the spin laser and the effect polarization of the carrier population has on the lasing threshold. Most importantly, we will examine dynamic operation of the spin laser, for which there is still much to be observed.

BUCKET MODEL

We can understand the operation of a spin laser by first considering the conventional (spin unpolarized) laser. The bucket model of laser operation in Fig. 1 provides a visual aide. The bucket has a large opening toward the top, and smaller openings toward the bottom. As the bucket is filled with water, there will be a slight amount of water leaking due to the smaller openings. Once the bucket is filled to the level of the large opening, water will begin to pour out, resulting in loss at a much greater.

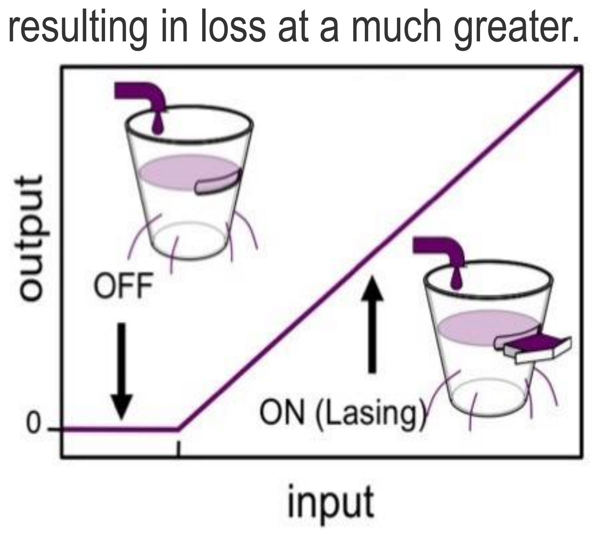

Figure 1: The bucket model for conventional lasers. The plot shows the photon output density of the laser's gain cavity. On the input axis there is a marking to represent the lasing threshold. This signifies the rate of carrier injection that triggers the lasing process, i.e., production of coherent light.

This bucket model serves as an analogy for conventional laser operation. A laser is pumped with carriers (electrons and holes) similar to the water pumped into the bucket. When an electron fills a hole (recombination), a photon is emitted. At a low pumping rate, the recombination is predominately spontaneous and does not occur at a significant rate (like the small holes in the bucket). As the pumping rate is increased, a phenomenon known as stimulated emission will occur. At this point, the emission of photons becomes significant (like the water overflowing out of the large opening). The rate of carrier injection required for sustainable stimulated emission is the lasing threshold.

To understand how the spin laser operates, we must adapt the bucket model. In Fig. 2, the bucket now has a porous divider inside of it. There are two sides of the bucket we can fill, say, with hot and cold water. If we attempt to only fill one side of the bucket to a higher level than the other side, the pores in the divider will allow the water to leak, and the levels of water will be comparable if left to equalize for a characteristic period of time. However, if we fill one side at a fast enough rate, we have the ability to make the bucket overflow with less water than before, and we can choose whether the overflowing water is hot or cold.

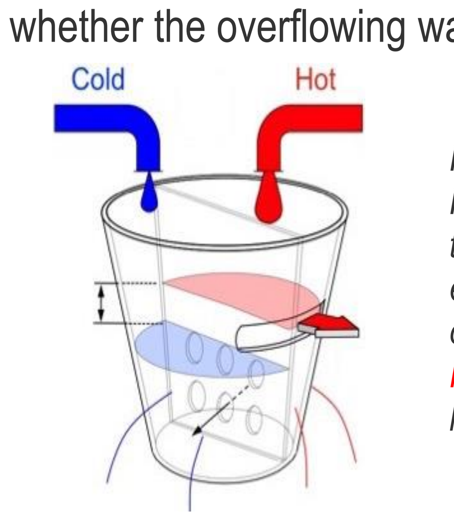

Figure 2: The bucket model for a spin laser. Hot water is injected at rate greater than the time it takes for the water levels to achieve equilibrium. Therefore, we have significant overflow with less water than was need in Fig. 1. The analogous property for a spin laser is known as threshold reduction.

To relate the new bucket model of Fig. 2 to the operation of a spin laser, we must understand a quantum mechanical property of electrons and holes known as spin angular momentum. For our purposes, it suffices to know that electrons and holes can be one of two types: spin up (+) and spin down (-) (think hot and cold water). Carriers have the ability to change spin orientation, so the spin of an electron should not be thought of as a static property (think leakage through the divider within the bucket). Spin relaxation time is the parameter of this property (0 implies instantaneous relaxation, ∞ implies static spin orientation).

In a conventional laser, the injected carrier populations are balanced. In a spin laser, we create an imbalance in the populations that will result in a reduction of lasing threshold (think less water to make the bucket overflow). We will actually have two lasing thresholds (J_{T1} and J_{T2}): one for left-circularly polarized light and another for right-circularly polarized light. In Fig. 3, we see how these thresholds are split, with one above the conventional laser's lasing threshold and one below. We end up with 3 regimes of operation. In the 2nd regime, neglecting the spontaneous emission of photons, the output light is 100% circularly polarized (think only hot water overflowing in Fig 2).

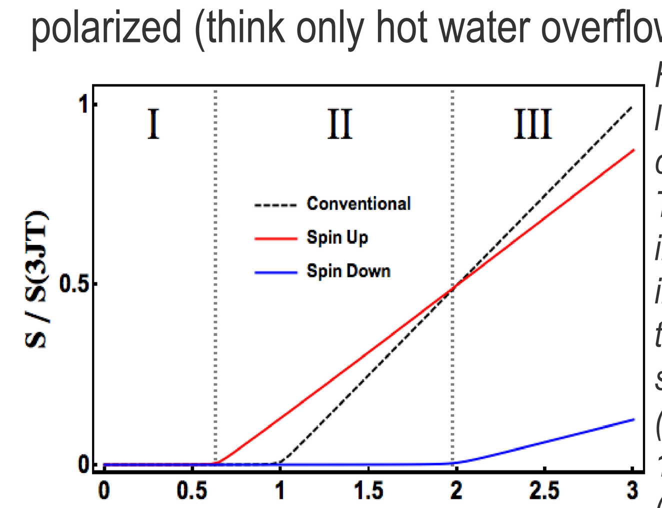

Figure 3: Comparison of lasing thresholds for conventional and spin lasers. This laser has 75% carrier imbalance. The plot is split into three regimes defined by the spin laser: (I) no stimulated emission of light (II) stimulated emission of 100% circularly polarized light (III) emission of both helicities of light.

MOTIVATION FROM EXPERIMENT

It has been shown experimentally that a small degree of polarization in the injected carriers can result in a high degree of polarization in the emission of circularly-polarized light. At room temperatures, a group of physicists in Japan achieved 96% circular polarization of light with an optically pumped vertical-cavity surface-emitting laser (VCSEL) using a spin imbalance of 4% ($P_C=(I_{\sigma+}-I_{\sigma-})/(I_{\sigma+}+I_{\sigma-})$) in the excitation intensity (Fig. 4).

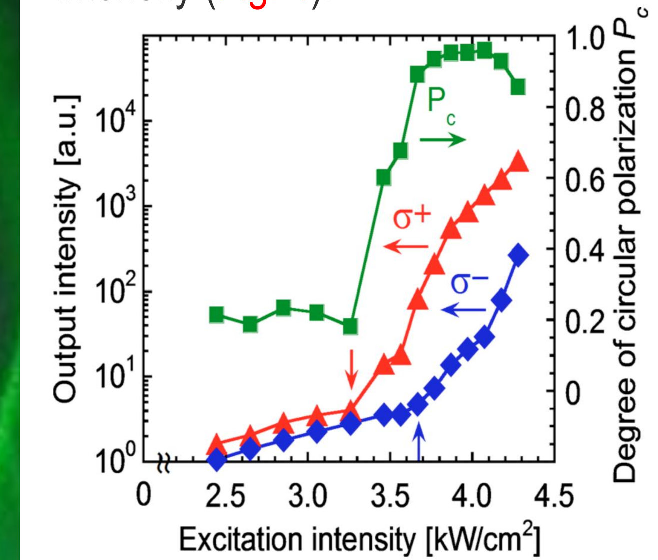

Figure 4: The red and blue curves represent the intensities of circular polarizations of output light as a function of excitation intensity. The red and blue vertical arrows mark the respective lasing thresholds for each helicity of light. The green curve is the degree of circular polarization in the output light. Photo credit: [3].

THRESHOLD REDUCTION

With our rate equation model of spin lasers (see ref. 2 for detailed discussion), we have reduced the lasing threshold by injecting an imbalance of carriers into the gain medium of the laser. While this effect was previously known, it had been believed that a 50% reduction in threshold ($r=(J_T-J_{T1})/(J_T)$, where J_T (J_{T1}) is conventional (spin) laser threshold) was the theoretical maximum [4]. The limit was derived under the assumption that the spin relaxation times of electrons and holes are equal. This, however, is not the case for many materials used in semiconductor lasers [5]. In Fig. 5, the effect of independent spin relaxation times for electrons and holes results in different threshold reductions. We have calculated from the rate equations a threshold reduction exceeding the previously reported limit, reaching as high as 55% threshold reduction. While the improvement is modest, our consideration of other processes in laser operation, such as the Auger process, have shown further improvements.

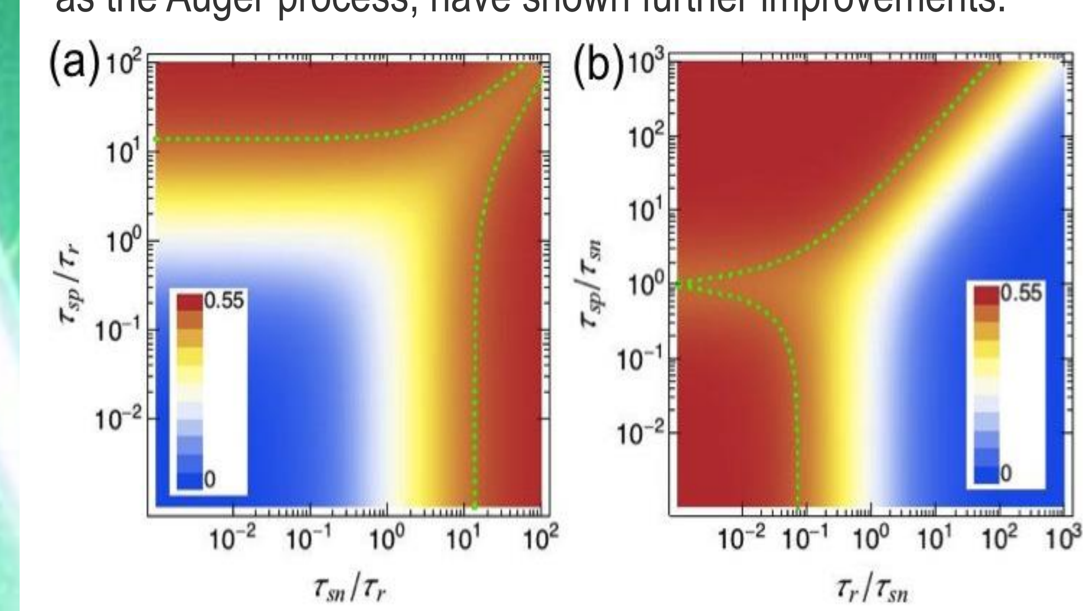

Figure 5: Lasing threshold reduction for (a) hole vs electron spin relaxation times (τ_{sp} and τ_{sn}, respectively) (b) τ_{sp}/τ_{sn} vs. ratio of recombination time (τ_r) to τ_{sn}. The green dashed lines represent 50% threshold reduction.

LARGE-SIGNAL ANALYSIS

So far, we have discussed static operation of lasers, that is, we turn them on and predict what happens after the system has reached equilibrium. More astounding effects can be predicted from the dynamic operation of a spin laser, that is, seeing what happens immediately after changing the state of the laser from off to on.

In Fig. 6, we see what happens when we inject carriers at a rate lower than the lasing threshold, then quickly switch the rate above the threshold. The laser will achieve a steady state after we do this, but there will be a period of transitory effects. We see in Fig. 6 oscillations in the photon output density, known as relaxation oscillations. These occur in all lasers when injection is changed abruptly.

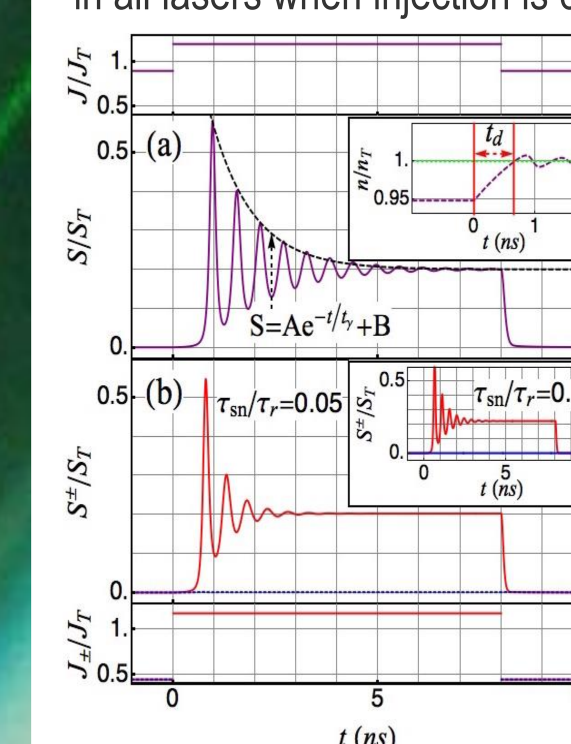

Figure 6: (a) The dynamic operation of a conventional laser (the carrier injection is shown above) with the exponential fit shown for clarification. [inset] Fluctuation of carrier density. (b) The dynamic operation for a spin laser for the same parameters used in (a). (Carrier injection shown below. The injection is initially balanced, then become 100% polarized when the laser is turned on.) [inset] dynamic operation for a different spin relaxation time.

The improvement we see in spin lasers is how quickly the relaxation oscillations are damped. We have quantified the damping with an exponential fit (described in Fig. 6). In the exponent, we calculate a term known as the decay time. In Fig. 7, we plot the decay time as a function of the ratio of electron spin relaxation time to recombination time (τ_{sn}/τ_r), with τ_r held fixed. Counterintuitively, we see a minimum in decay time (fast damping) for a value of electron spin relaxation that is not an extreme value (zero or infinity), as one might have presumed.

In Fig. 7, we also see an increase in bandwidth as the spin relaxation time is increased. A larger bandwidth allows for more information to be transferred in a given time interval (think of internet speeds).

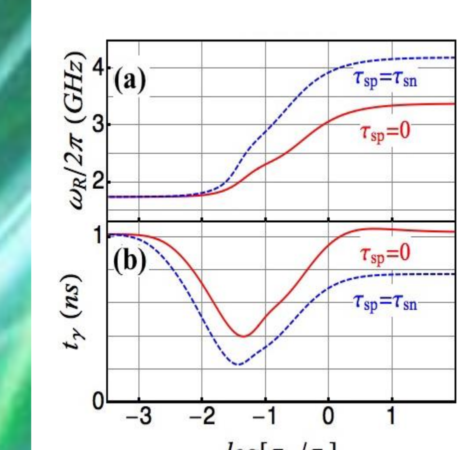

Figure 7: We consider two systems: spin relaxations set equal and hole spin relaxation set to zero. (a) Bandwidth and (b) decay time calculations for both systems as a function of electron spin relaxation time.

REFERENCES

1. See A. Einstein, "On the quantum theory of radiation."
2. J. Lee, S. Bearden, E. Wasner, and I. Zutic, Appl. Phys. Lett. 105, 042411 (2014).
3. S. Iba, S. Koh K. Ikeda, and H. Kawaguchi, Appl. Phys. Lett. 98, 081113 (2011).
4. M. Holub, J. Shin, D. Saha, and P. Bhattacharya, Phys. Rev. Lett. 98, 146603 (2007).
5. I. Z□utic, J. Fabian, and S. Das Sarma, Rev. Mod. Phys. 76, 323 (2004).

ACKNOWLEDGEMENTS