Self-driving lab discovers high-efficiency directional incoherent emission from reconfigurable semiconductor metasurfaces

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Abstract: We discover high efficiency (77%) steering of incoherent emission from reconfigurable semiconductor metasurfaces by engineering the spatial refractive index profile of the metasurface resonators using autonomous experiments driven by generative models and active learning.

Spatial control of incoherent (thermal) light emission has been a critical challenge in the field of optics with far ranging applications from remote sensing to holographic displays. Reconfigurable metasurfaces operating in a similar fashion to phased-antenna arrays have been used to dynamically steer coherent (laser) beams [1] but the same principle cannot be used to steer incoherent light [2]. We recently demonstrated that the far-field profile of incoherent light emission (photoluminescence – PL) from within the metasurface can be varied by imposing specific spatially varying refractive index profile on the metasurface using a spatially structured optical pump beam. However, identifying the specific form of refractive index (pump) profile to optimally steer emission in a desired direction is challenging, due to exponentially large number of possible profiles, of which only a small number steer emission efficiently. Here, we discover high-efficiency (up to 77%) steering of PL from reconfigurable metasurface by creating a self-driving lab, where autonomous experiments are driven by machine learning (ML) to discover the optimal spatial refractive index pattern to be imposed on a light-emitting GaAs metasurface [2]. Our ML framework uses an active learning agent exploring refractive index profiles in a low-dimensional latent space learnt by a generative model (variational autoencoder – VAE). Our autonomous experimental platform couples to the active learning agent, imaging a refractive index profile on the metasurface to generate a directional emission of incoherent light. Our self-driving lab efficiently explores the space of arbitrary aperiodic 1-D pump-induced refractive index profiles to maximize the directivity of emission towards a given angle, discovering profiles that go beyond human intuition and yielding scientific insight into the process of incoherent emission steering.

We first demonstrate, as a baseline, PL steering with a human-intuition driven saw tooth (blazed grating) refractive index profiles imposed on the semiconductor metasurface (Figure 1). We find these profiles to show a low steering efficiency of 3%, i.e., only 3% of the emitted light is steered into a direction of our choice, as measured by our metric directivity ($D = f(\theta)/\sum_{\theta} f(\theta)$, where f(θ) is the signal going towards a particular steering angle, θ). The grating orders represent a fixed spatial frequency for each steering angle based on momentum conservation of light emission, defining the local density of states (LDOS) of the metasurface emitter (Fig 1C). The metasurface consists of an array of GaAs resonators with embedded InAs quantum dot emitters placed on an $Al_{0.3}Ga_{0.7}As/AlAs$ distributed Bragg reflector (DBR). The reconfigurable GaAs metasurface was designed to achieve nearly 2π phase coverage in reflection at the emission wavelength of 1250nm, based on the free-carrier induced index tuning upon absorption of a strong optical pump. We excite the metasurface with a strong optical pump (800nm, 80fs pump) that induces a refractive

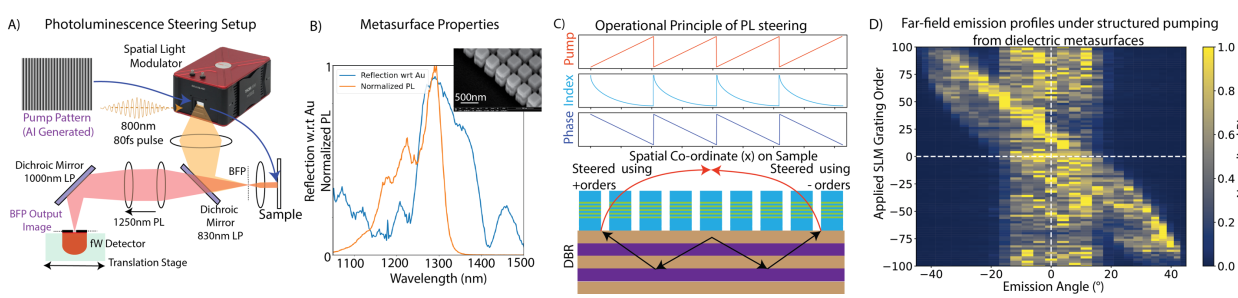

Figure 1: A) Photoluminescence steering setup where a semiconductor metasurface sample is optically pumped using a spatially structured 80fs, 1 KHz repetition rate at 800nm with 2-3mJ/cm^2 by imaging an ML generated pump pattern loaded into a spatial light modulator (SLM). The far-field emission pattern is imaged by translating a point detector in the back-focal plane with lock-in amplifier chopping the pump beam as described in [2] **B)** Semiconductor metasurface properties: The reflection and photoluminescence spectra of the nanofabricated metasurface of GaAs resonators (tilted scanning electron microscopy image inset at the top right corner) is plotted as a function of the wavelength. The peaks in reflection match with the emission peaks from the metasurface. **C)** Operational principle of PL steering demonstrating the effect of spatial structure on optical pump intensity inducing a spatial refractive index pattern, resulting in a spatial phase profile on the metasurface. The spatial phase profile generates a momentum shift to the light emission steering PL from the InAs quantum dots embedded inside the resonators. **D)** PL steering from metasurface demonstrated over 80° field of view as a function of the SLM grating order applied on the metasurface. The emission profiles are normalized over the field of view for each pump pattern.

index change through free-carrier generation in the GaAs resonators to optically induce a phase shift in the resonant state resulting a spatially momentum (phase gradient) profile which is used to steer the light emission (Figure 1A, [2]).

Given the limitations of periodic refractive index profiles, we explore aperiodic profiles by imposing aperiodic pump patterns on our metasurface using a generative model and active learning, rapidly evaluating the pattern with the autonomous experiment setup. Fig 2A shows our ML workflow. We trained 2 separate VAEs; one of which had the training data restricted to periodic patterns (periodic VAE) while the other had arbitrary aperiodic 1-D curves (aperiodic VAE) to generate arbitrary pump patterns to be imposed on the SLM, using a latent space of 4 variables. The active learning agent uses a small pre-defined training set (blue dots in Fig 2B) of pump patterns (encoded in the VAE latent space) and their corresponding directivities, to predict directivities across the entire latent space of the VAE. The most promising point in latent space, as identified by an acquisition function, is measured for rapid evaluation with our autonomous experimental platform to find points in latent space that have significantly improved steering efficiency compared to the training set used to initialize the active learning agent (Fig 2B). From the resulting optimized pump patterns (Fig 2B), we observe that these patterns are a combination of a lens and a grating spatial phase profile which significantly improve the directivity of the metasurface emitter by an order of magnitude when compared with human intuition driven grating order pump patterns. The generative capability of the VAE combines features of simple pump patterns in multiple ways to generate a large set of complex patterns with only a small fraction of these patterns steering the PL. Figure 2C shows that the active learning agent efficiently finds a variety of patterns to maximize the PL directivity towards each steering angle in FOV resulting in 12x greater efficiency when compared to the traditional blazed grating pump patterns in Fig 1D. Extending the generative capability using the aperiodic VAE, we now see an even greater increase (44% relative to periodic VAE) in the directivity of PL resulting in a maximum of 77.3% steering efficiency at 0° emission angle. In conclusion, we have developed a self-driving lab coupling autonomous experiments with generative models and active learning to discover improved steering efficiency, and setting the foundation to automate the discovery of fundamentals of light-matter interactions.

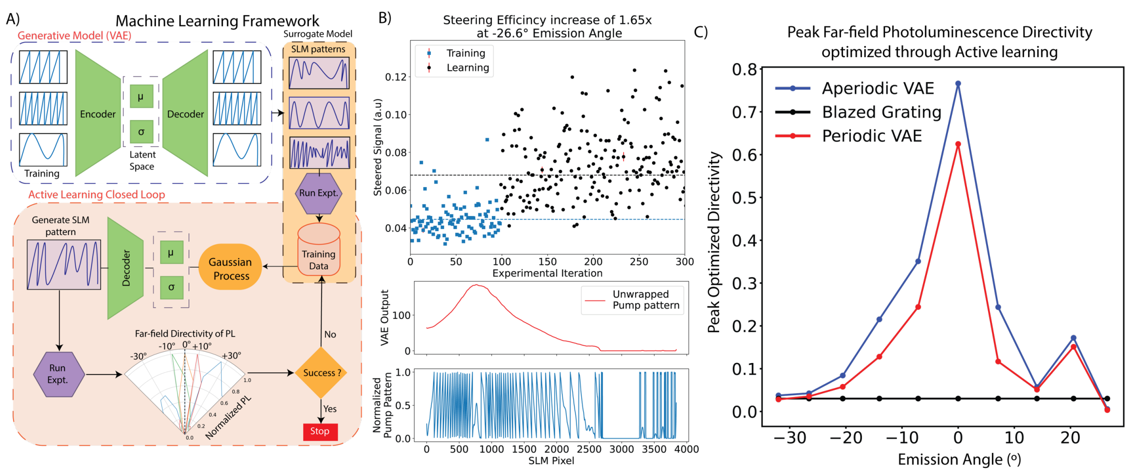

Figure 2: A) Machine learning framework defining the workflow to combine a variational autoencoder and an active learning agent (Bayesian optimizer) to learn the far-field PL steering principles. **B)** Result of the active learning to steer PL towards -26.6°: the top panel represents the active learning process (blue dots - the training data, black dots – points selected by active learning). The bottom two panels represent the final optical pattern (red-VAE output) for optimal steering and the phase wrapped pump pattern projected onto the sample (blue). **C)** The result of optimizing for directivity along each of the steering angles using periodic VAE (red), aperiodic VAE (blue) and classic blazed grating (black).

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