Experimental Realization of Supersymmetric Laser

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Abstract: A multimode, chaotic, and broadband emission is an undesired characteristic of laser arrays which is an adverse effect of supermodes in coupled waveguides. Employing optical supersymmetry, we experimentally demonstrate single mode lasing in arrays of supersymmetric lasers where a superpatner array eliminates undesired lasing modes.
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First proposed in quantum field theory, supersymmetry (SUSY) is a unique symmetry of space and time that resolves unanswered questions of standard model, e.g the origin of mass scales or the nature of vacuum energy. In this context, SUSY treats bosons and fermions on equal footing by conjecturing a partner particle for each particle in the nature both of which share many of the same properties but the crucial one i.e. spin [1]. SUSY's existence is still being sought in high-energy experiments, but it has yet to be detected. However, the concept of SUSY has been successfully adapted in non-relativistic areas such as quantum mechanics [2] and recently in optics [3]. In optics (quantum mechanics), SUSY stablishes a systematic approach to obtain a superpartner refractive index (potential) with an identical eigenspectrum to that of the main index of refraction (potential), except the ground eigenvalue which is annihilated from the eigenspectrum of superpartner refractive index (potential) [3]. Indeed, it has been shown that optical SUSY provides a versatile platform to design optical devices with characteristics at will by which for example a mode division multiplexer in a passive optical network has been experimentally realized [4]. Recently, the concept of optical SUSY has been extended to active devices, e.g. lasers [5]. In this framework, SUSY is applied to laser arrays to achieve a single mode, low divergence, low threshold, and high power integrated laser. In fact, investigations on laser arrays to fulfill high power lasers with such characteristics dates back to a few decades ago [6, 7]. However, the main drawback of laser arrays is their broadband and chaotic emission spectrum. When identical single transverse mode laser cavities are juxtaposed in close proximity of each other to construct a laser array, the strong coupling between individual laser cavities results in breaking their single mode into multimode profiles, i.e. supermodes. Thus, a chaotic laser emission with a large beam divergence and a broad linewidth underperforms the operation of laser arrays [8]. Although removal of longitudinal modes associated with each laser cavity has been realized by practical approaches such as distributed Bragg grating or parity time symmetric structures, elimination of supermodes in laser arrays is a big hurdle that has remained challenging up to date [9]. Among several approaches to control the emission of supermodes [10, 11], SUSY introduces a systematic approach [5]. In this respect, a superpartner array with an extra loss is judiciously designed such that it supports all supermodes of the main array but the fundamental one. When superpartner array is placed in a close proximity of the main array, all undesired supermodes of the main array are coupled into the superpartner where they experience a large loss which necessitates them a larger threshold than fundamental mode to lase. Thus, only the fundamental supermode that is not coupled to the superpartner array lases in the main array by applying a low threshold power which sharpens the emission spectrum of the laser array. In this work, by employing the concept of SUSY laser arrays for the first time we experimentally realize such a single mode SUSY laser array that operates in its fundamental mode at about 1493 nm with a narrower linewidth compared to a typical laser array. We believe that our finding paves the road towards high power laser arrays with a low lasing threshold, a small beam divergence, and a narrow emission linewidth.

Figure 1a illustrates a schematic representation of designed laser arrays along with their dimensions where the left array in orange demonstrates the main array supporting five supermodes, while the right green array represents the superpartner array supporting the four undesired supermodes of the main array. The simulated five supermodes of the main array is shown in Fig. 1b along with their calculated effective refractive indices. In this figure, the first row shows the optical intensity in waveguide cavities and the second row demonstrates their corresponding electric field profiles. The superpartner array was judiciously designed based on optical SUSY theory [3, 5] such that it supported all modes of the main array except the fundamental one with $n_{eff} = 2.6608$. To fabricate the designed laser

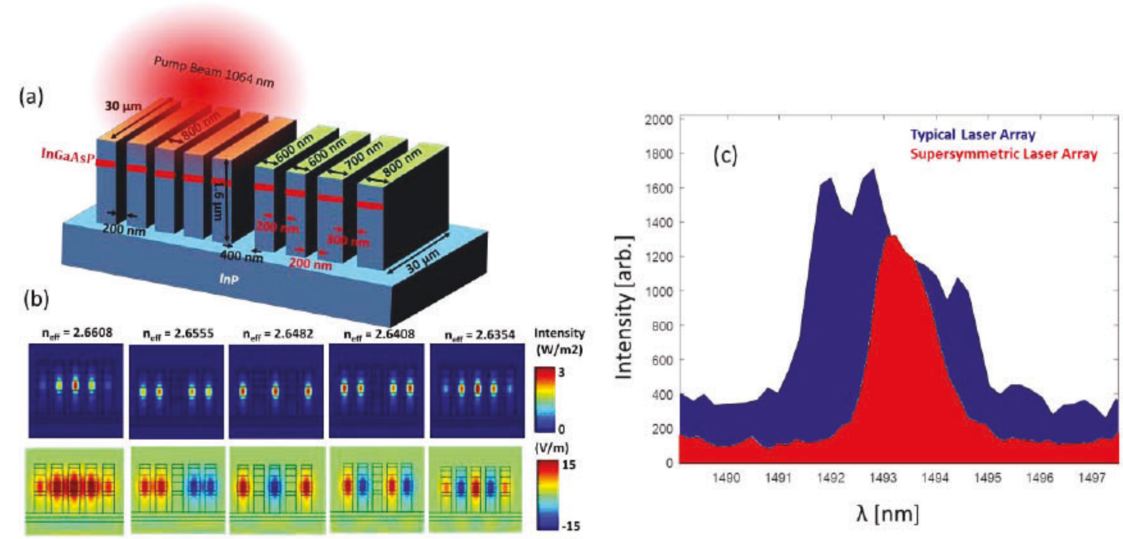

Fig. 1a. Schematic illustration of a supersymmetric laser array where only the main array is exposed to the pump beam. b. Simulated intensity (row 1) and electric field profiles (row 2) of main array with five coupled lasers along with their corresponding effective indices. c. Measured spectrum of laser array without superpartner (blue) and with superpartner (SUSY laser array) (red) where in supersymmetric laser, superpartner sharpens the broad spectrum of the laser array by eliminating the four undesired supermodes.

arrays, hydrogen silsesquioxane (HSQ) solution in methyl isobutyl ketone (MIBK) was first spin-coated on InP-InGaAsP-InP wafer as a resist; the wafer was then patterned using electron beam lithography. The structures were developed using tetramethylammonium hydroxide (TMAH) and subsequently transferred to the wafer through a reactive-ion-etching (RIE) process. InGaAsP comprises the active medium of the laser with the bandwidth spanning the spectral region between 1290 and 1600 nm. For testing samples, a pump beam with the wavelength of 1064 nm shined the sample where the superpartner array was completely withheld from exposing to pump beam by using a knife-edge and the emitted lasing spectra was collected by a monochromator (details of experiment can be found in [12]). It is worth mentioning that intentionally withholding the superpartner array from exposing to pump beam prevents the associated waveguide cavities from lasing and therefore the four undesired supermodes undergoes a larger loss than gain in superpartner array. As a result, only the fundamental mode is expected to lase. Figure 1c compares measured spectrum of a typical laser array with five coupled waveguide cavities (blue) to that of a SUSY laser array where the superpartner array eliminates the undesired supermodes leading to a narrow spectral emission (red).

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