Single Mode Supersymmetric Laser Array

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Abstract: Multimode emission adversely affects phased-locked laser arrays resulting in chaotic behaviors. Utilizing optical supersymmetry, we experimentally demonstrate a single mode laser array where a superpartner array eliminates undesired higher order transverse modes.
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Phase locking of an array of lasers has been a subject of intense research for realizing high output power and low lasing threshold integrated lasers [1]. However, the performance of such phased-locked laser arrays is adversely dominated by supermodes, when the individual array elements (i.e. waveguide lasers) are placed in close proximity of each other to construct such kind of laser [2]. In these arrays, the strong coupling between adjacent identical single transverse mode lasers breaks the degeneracy between them and results in splitting their single mode into several transvers modes i.e. supermodes. Thus, a chaotic laser emission with a large beam divergence and a broad lasing spectrum underperforms the operation of laser arrays [3]. 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 challenge up to now [4]. Among several approaches to control the emission of supermodes, supersymmetry (SUSY) introduces a systematic strategy [5,6]. First emerged within quantum field theory as a means to treat bosonic and fermionic particles on equal footing by considering their corresponding superpartner particles, and then developed to complete standard model by resolving unanswered questions such as the origin of mass scales or the nature of vacuum energy [7], SUSY has been also successfully adapted to nonrelativistic quantum mechanics. In this context, SUSY stablishes a systematic approach to obtain a superpartner potential with an identical eigenspectrum to that of the main potential, except the ground eigenvalue which is annihilated from the eigenspectrum of superpotential. It has been recently proposed that the same SUSY concept can be applied to optics where for any distribution of refractive index, a superpartner index of refraction can be found such that it yields the same eigenspectrum of the main index profile but with removed ground eigenvalue [8]. Indeed, it has been shown that optical SUSY provides a versatile platform to engineer optical structures with desired characteristics by which for example a mode division multiplexing in a passive optical network has been experimentally demonstrated [9]. Recently, the concept of optical SUSY has been extended to active optical structures e.g. laser arrays where undesired supermodes can be suppressed in favor of the fundamental mode [10]. In this regard, a superpartner array with 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 requires them a larger threshold than fundamental supermode to lase. Thus, only the fundamental supermode that is not coupled to the superpartner array lases in the main array by applying a low pump power. Here by employing the concept of SUSY laser arrays, for the first time we experimentally realize such a single mode SUSY laser array which operates in its fundamental mode at about 1493 nm wavelength with a narrower linewidth compared to a typical laser array. We believe that our findings pave the road towards high power phase-locked laser arrays with a low lasing threshold, a small beam divergence, and a narrow linewidth emission.

Figure 1a shows a schematic representation of designed laser arrays with corresponding 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 illustrated in Fig. 1b along with their corresponding effective refractive indices in which the first row shows the optical intensity in waveguide cavities and the second row demonstrates their associated electric field profiles. The superpartner array was judiciously designed based on optical SUSY theory [8,10] such that it supported all modes of the main array except the fundamental one with $n_{eff} = 2.6608$. To fabricate the designed laser 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

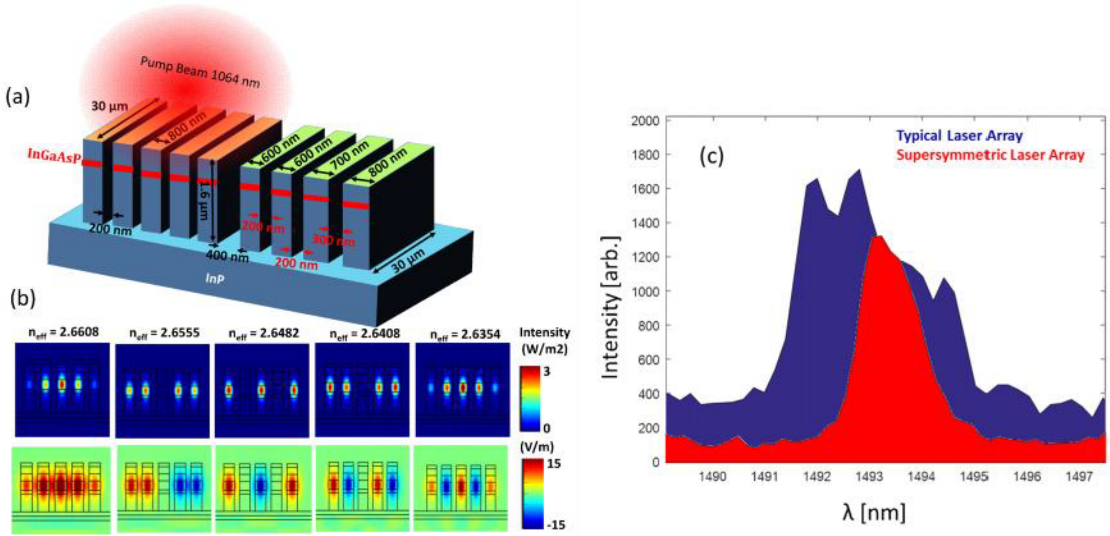

Fig. 1a. Schematic representation of a supersymmetric laser array where only the main array is exposed to the pump beam. b. Simulated intensity (row 1) and electric field profiles (row 2) of main array with five coupled lasers along with their corresponding effective indices. c. Measured spectrum of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

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 1064 nm excited 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 [11]). 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 narrower spectral emission (red).

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