We demonstrate strongly polarized photoluminescence (PL) from Er3+ ions embedded in the plasmonic nanocavity arrays as reported recently [Choi *et al*., Nano Lett. **16**, 5191 (2016)]. The precise positioning of the Er3+ layer within the nanocavities in respect to the node and antinode of the electromagnetic field modifies the PL spectral shape and allows to obtain linearly polarized emission with a 98% degree of polarization. The observed PL is caused by a single component of the dipole moments in the Er3+ emitters, by an anisotropically controlled local density of states (LDOS).

Randomly oriented dipoles uniformly distributed in free space emit unpolarized photons which are isotropically propagating in a homogeneous LDOS environment. The spectral shape and the efficiency of the emission are intrinsic properties of emitting materials. However, the radiation from dipoles placed in an inhomogeneous LDOS environment can exhibit strongly modified emission angle, polarization, and spectral shapes. These properties also depend on whether the origin of the radiation is an electric dipole (ED) or a magnetic dipole (MD) because the electric-LDOS (E-LDOS) and the magnetic-LDOS (M-LDOS) are not equal to each other in an inhomogeneous environment.1) Although the MD transition is a high-order transition negligibly contributing to PL, trivalent lanthanide ions such as Eu3+, Tb3+, and Er3+ exhibit strong MD contributions in their PL spectra.2)

Recently, we reported a new approach to manipulate E- and M-LDOS in PL from Er3+ ions in the 1.5 m band by using plasmon-enhanced nanocavity arrays with narrow and deep trenches.3) The Er3+ embedded plasmonic nanocavities presented several significant characteristics: (1) Several-10-fold PL enhancement was achieved by selectively controlled ED and MD transitions of 4*I*13/2→4*I*15/2 in an Er3+:SiO2 system. (2) By tuning the resonant wavelength and controlling the position of the Er3+ layer in the nanocavities, the spectral shape of the PL was significantly modified. (3) Magnetic as well as electric Purcell effects4) were experimentally observed by measuring the lifetime of the PL. (4) the PL components of the ED and MD transitions in bulk Er3+:SiO2 were clearly separable that had not been explicitly reported earlier. However, there are no reports on the polarization state due to the LDOS control. In this work, we present results on the polarization properties of PL observed from the plasmonic nanocavity arrays. The ED- and MD-enhanced PL from the nanocavity arrays with a precisely positioned Er3+ layer show linearly polarized emission with a high degree of polarization and a unique spectral shape, which reflects highly controlled E- and M-LDOS.

Refs.5,6) discussed the polarization properties in the MD transition.The ED and MD transitions of Eu3+ ions embedded in a stacked thin-film system exhibited specific momentum- and polarization-dependent PL patterns. The polarization dependence originates from the difference in the self-interference due to reflections at the interface between the dipoles parallel and perpendicular to the films being explicitly observable at large observation angles. However, the polarization dependence was not salient, and the emission from the dipoles oriented in all directions was largely mixed.

Figure 1 presents a schematic of the nanocavity arrays discussed in this study. Rectangular cavity resonators filled with SiO2 with a width *W*, a depth *D*, and an infinite length in the *y*-direction are covered with Au and are periodically arranged with a period *P*. The polarization angle ** is defined so that **=0° corresponds to the transverse magnetic (TM) polarization and **=90° corresponds to the transverse electric (TE) polarization. A rectangular cavity is a terminated metal-insulator-metal (MIM) waveguide. A MIM waveguide of a sufficiently narrow width compared with the wavelength **[*W*≪**/(2*n*), where *n* is the refractive index of SiO2] only allows the propagation of a TM-polarized plasmon mode and forbids the presence of any TE-polarized mode.7) As a result of the reflection at the entrance and the bottom of the waveguide, the plasmon mode with a wavelength **p exhibits standing waves when *D*≈(1/4)**p, (3/4)**p, etc. Thus, the TM-polarized electromagnetic (EM) energy is strongly confined and displays a sinusoidal profile in the narrow cavities. The dimensions of the nanocavities were determined to be *W*=100 nm, *D*=550 nm, and *P*=800 nm, so that the second-order resonance [*D*≈(3/4)**p] appeared at the free-space wavelength of 1.53 m. The cavities contained a 20-nm-thick Er3+-doped layer at a depth, *T*, from the entrance.

Here, we discuss two extreme cases. One is the position of the Er3+ layer at the E-LDOS maximum, and the other − at the M-LDOS maximum. Analytical formulations for the LDOS of a simple multi-layer system8,9) are not applicable to complicated geometries such as the nanocavities in this work. Here we discuss the LDOS on the basis of a generalized reciprocity formulation by Taminiau *et al*. [Eqs. (S16) and (S17)].6) The emission rate for each polarization in the −*z* direction from an emitter embedded in a material can be determined from the local field at the emitter's position under the illumination in the −*z* direction with the corresponding polarization.

Figure 2(a) shows a schematic for the positions of the Er3+-doped layers in the E- and M-LDOS maxima configurations (left) and the corresponding EM fields (right). Spatially distributed in sinusoidal forms but with a reversed intensity pattern along the z-direction, the electric (E) and magnetic (H) fields are enhanced by two orders of magnitude compared to that of incidence. The PL intensity *I*PL of an isolated emitter is proportional to |***d***ED•***E***|2 and |***d***MD•***H***|2, where ***d***ED and ***d***MD are the dipole moments of ED and MD, respectively.10) At the position of the *E* field maximum, the *H* field vanishes, and vice versa. For the E- and M-LDOS maxima configurations, the Er3+ layers are positioned at *T*=365 nm and *T*=155 nm, respectively. Figure 2 (b, c) displays the field intensity spectra at the two positions. The E-LDOS maximum peaks at 1.53 m, while the *H* field is close to zero. The M-LDOS maximum shows the opposite pattern. The EM field distribution directly represents the LDOS environment and governs the ED and MD transition rates.

We discuss the polarization of the PL in the nanocavities based on the considered *E* and *H* field distributions. For the E-LDOS maximum configuration, since the *Ex* component is dominant (*Ez* is negligible3) and *Ey* is forbidden), *I*PL∝|*d*ED*xEx*|2 and the emission has the *Ex* component. In the M-LDOS maximum configuration, *I*PL∝|*d*MD*yHy*|2 and the emission has an *Hy* component because the magnetic field components, except for *Hy*, are forbidden. Therefore, both the far-field emissions from the E- and M-LDOS maxima are TM-polarized. If we set a polarizer, we can expect that the intensities of the PL are proportional to cos2*θ*.

The PL spectra from the patterned 300×300 m2 area were measured at the normal incidence under excitation using a continuous-wave laser with a wavelength of 523 nm, which is resonant for 4*I*15/2→ 2*H*11/2 or 4*S*3/2 absorption transition in Er3+ ions.11) To evaluate polarization of PL, we inserted an angle-variable wire-grid polarizer with an extinction ratio of 1000 in the 1.53 m wavelength region in front of a spectrometer.

Figure 3 (a) and (b) show the PL spectra of the E- and M-LDOS maxima, respectively, as a function of the polarization angle *θ*. In both cases, the intensity is decreased with *θ*, and is extremely weak at *θ*=90°. The spectral shapes are very different from each other, and they agree very well with the respective ED and MD components of the PL of the bulk Er3+:SiO2, determined in our previous report.3) Fig. 3 (c) presents the normalized integral intensities for the wavelength range, which is an exact fit with cos2**. The degree of polarization defined as (*I*0–*I*90)/(*I*0+*I*90),12) where *I*is the wavelength-integrated intensities for ****is equal to 0.98 and 0.99 for the E- and M-LDOS maxima nanocavities, respectively. The result indicates that only the PL associated with the ED component oriented in the *x*-direction (*d*ED*x*) and the MD component oriented in the *y*-direction (*d*MD*y*) was selectively enhanced among the PL emissions of the randomly oriented dipoles in the *x-*, *y-* and *z*-directions. The small PL discernible in Fig. 3 (a) for *θ*=90° could be due to the imperfection of the structures such as the tapered rectangular shape observed in the scanning transmission electron microscope images.3)

The prominent ED- and MD-enhanced polarized emissions have not been observed in mirror configuration systems5,6) or nanoholes structures.13) This pronounced polarization is a direct proof that our nanocavities provide highly anisotropic E- and M-LDOS environments, which can be precisely controlled. From the results, we expect that the LDOS engineered nanocavities can provide new opportunities to develop reliable polarization-division multiplexing systems.14)

In summary, we have demonstrated linearly polarized emissions from E- and M-LDOS engineered nanocavities. The PL from the nanocavity arrays tuned to the Er3+ PL peak wavelengths showed a degree of polarization of at least 98%. It is noted that the observed unique PL properties in the radiative environment with extremely anisotropic LDOSs are discussed for the first time

**Address to Editors**

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Dear Editors,

We are pleased to submit our Manuscript entitled “*Strongly polarized emissions from selectively controlled electric and magnetic dipole transitions in Er3+ ions*” by the author’s list for consideration as an original article in the *Journal*.

The artificial nanostructures reveal unique and tunable optical properties. There is an increasing interest in the modification of the optical properties such as spectral shape, intensity, and polarization by controlling the radiation field in the nanostructures. Recently, we reported a new approach for electric- and magnetic-local density of states (LDOS) manipulation of photoluminescence from lanthanide Er3+ ions in the 1.5 m band by plasmon-enhanced nanocavity arrays [Choi *et al*., Nano Lett. **16**, 5191 (2016)]. However, polarization due to the LDOS control has not been investigated.

In this study, we found that the emission from the Er3+ ions in the nanocavity arrays is strongly linearly polarized due to the extremely anisotropic radiation fields. We present on the polarized properties with a high degree of polarization and reveal their origin from the contributed dipole moments in the Er3+ emitters.

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