Confined Visible Optical Tamm States

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ABSTRACT

Optical Tamm states are 2D electromagnetic modes propagating at the interface between a Bragg mirror and a metallic film. When a thin (a few tens nm) metallic micron—radius disk is deposited on a Bragg mirror, optical Tamm states can be confined below the disk surface, creating a Tamm-states cavity. We describe here the photoluminescence properties of colloidal semiconductor nanocrystals embedded in a Tamm cavity. Tamm states confinement effects are demonstrated and analysed as a function of the disk diameter, and compared with finite-elements simulations.

Keywords: optical Tamm states, fluorescence, nanocrystals

INTRODUCTION

An optical analog to electronic surface states described by Igor Tamm in 1933 [1], optical Tamm states were proposed after 2003 as electromagnetic modes confined at the interface between two Bragg mirrors [2] or at the interface between a Bragg mirror and a metallic film [3,4, 5] (fig. 1(a)). Optical Tamm states offer strong in-plane confinement of the electromagnetic field which can be used to enhance light-matter interaction, such as light emission by fluorescent molecules [5]. As compared to surface-plasmon-polariton (SPP) modes, the relation dispersion of Tamm states intersects widely with the light cone (fig. 1(b)), so that these states can be coupled to the propagating electromagnetic modes, without the need for Kretschmann configuration or grating

coupling [6], and in both s and p polarizations. Various uses of Tamm states have been proposed recently, for instance for the fabrication of logic gates [7], photovoltaics systems [8], optimized single-photon sources [9], transparent electrical contacts [10], nanolasers [11] or for biological detection [5].

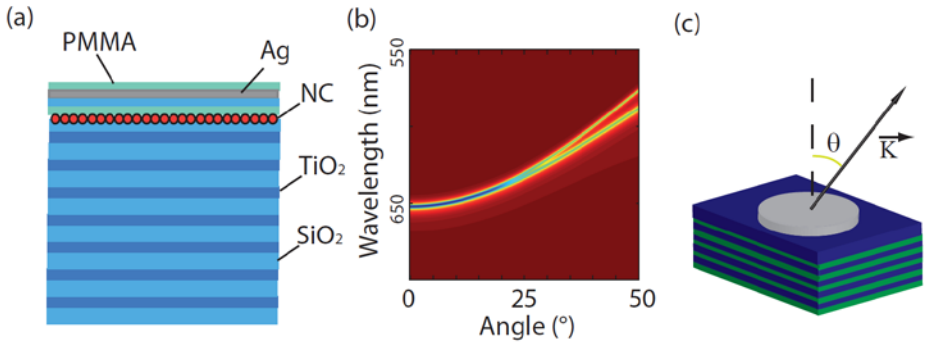

Figure 1. (a) Schematic of a 2D Tamm state structure ; (b) simulated specular reflection spectrum of a 2D Tamm state structure as a function of the incidence angle θ, with Tamm structure thicknesses as described in the text, and indices resp. 1.35 for SiO2, 2.32 for TiO2, 1.5 for PMMA, and Palik's values for Ag.

When a micron-sized metallic disk is deposited on top of a Bragg mirror (fig. 1(c)), confined Tamm states appear below the disk. This was demonstrated in 2011 for Tamm states in the near infrared domain (850 nm [12, 11] to 1,5 µm [13]). For a single epitaxial quantum dot located at the center of the disk structure, either enhancement of inhibition of the radiative decay has been evidenced, depending on the spectral agreement of the dot with the 0D Tamm plasmon mode [9,12]. For 0D Tamm plasmon structures including quantum well layers, laser threshold effects have been demonstrated [11].

In this paper, we describe the fabrication of 0D Tamm states structures in the visible domain coupled to colloidal semiconductor nanocrystals. We first detail the characteristics of the fabricated structures and the measurement principle. We then show the measured emission spectroscopic properties and compare them with simulated data.

EXPERIMENT

We fabricated 6 $\lambda/4n$ bilayers of TiO_2/SiO_2 (thickness), finishing with an upper SiO_2 layer of thickness $\lambda/4n + d$ with here d = 89 nm. A dense layer of fluorescent CdSe/CdS nanocrystals [14] was deposited and covered by 54 nm of polymethylmetacrylate (PMMA, optical index 1.5) and 49 nm of silica (instead of just 103 nm of silica as direct deposition of silica on nanocrystals would damage them). Silver 45-nm-thick disks of various diameters were deposited by photolithography (after Ag deposition, no lift-off of the remaining resist and Ag layer around the disks was performed in order to avoid for the disk radiation to be hidden by the radiation from the surrounding nanocrystals). Finally, a 50-nm (PMMA) polymer layer was deposited on the sample in order to protect silver from oxidation.

Fig. 1(b) plots the specular reflection spectrum of the corresponding 2D structure (as schematized on fig. 1(a)) as a function of the incidence-reflection angle, calculated by a transfer matrix method (FilmWizard software). Absorption by the optical Tamm state appears as a sharp dip on the calculated spectra. The Tamm-state in-plane wavevector k is thus related to the measured absorption angle by $k = k_0 \sin\theta$ with $k_0 = \lambda/2\pi$. The curve shows a parabolic shape with a wavelength maximum at $\theta = 0$. As expected from symmetry considerations, the two *s* and *p* polarizations are degenerate at $\theta = 0$; as the angle increases, the degeneracy is lifted. The thickness of the last silica layer was adjusted in order for the Tamm state resonance to match the emission wavelength of the fluorescent nanocrystals (640 nm).

The disks emission was characterized by photoluminescence microscopy with a 0.7-numerical aperture objective. The nanocrystals fluorescence was excited by a 470 nm continuous laser at 4 mW power. The emission was collected by the same objective and analyzed by an imaging spectrometer. The Fourier plane (back focal plane) of the objective was imaged on the entrance slit of the spectrometer, which provided the emission spectrum for different emission angles θ (with θ defined on fig. 1(c)). Again, the emission angle is related to the Tamm states wave vector distribution by $k = k_0 \sin\theta$.

RESULTS

Figure 2 shows the emission λ-θ distribution for a 2D structure (continuous Ag layer) and for Ag disks of various diameters. The emission from the nanocrystals into the Tamm state appears as a clear parabol between

625 and 605 nm, showing the good coupling of the nanocrystals with the Tamm modes. For the smaller disks (especially 2 µm), for wavelengths below 605 nm and above 625 nm, one also observes emission from the surrounding photoresist (not lift-off) into Tamm modes of the Ag layer surrounding the disk.

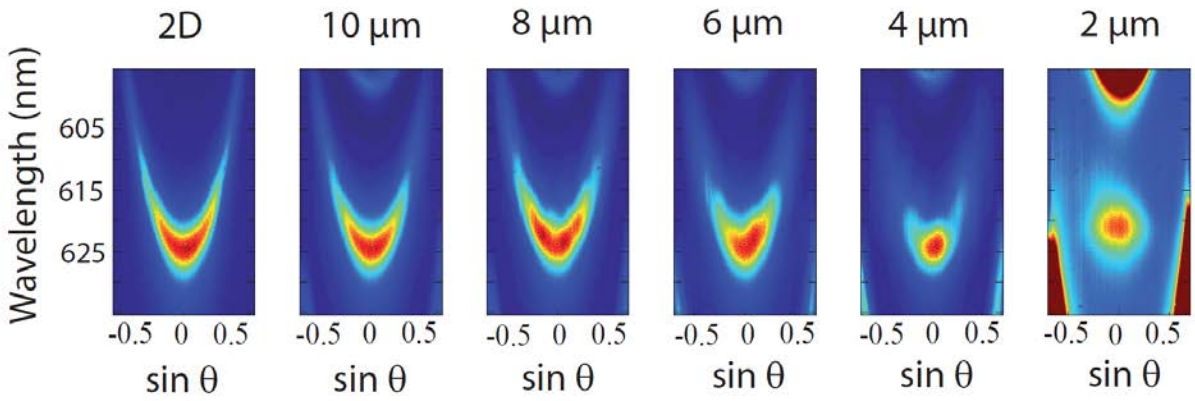

Figure 2. Fluorescence angularly-resolved spectra for nanocrystals in a 2D Tamm structure (left) and below Ag disks of various diameters from 10 to 2 µm.

For the 2D structure, the dependence of the Tamm state wavelength on the coupling angle is qualitatively well described by the simulation (fig. 1(b)), with about 25-nm blueshift from theory due to Bragg mirror fabrication imperfections. For the 10 and 8-µm disks, the Tamm λ-θ relation is similar to the 2D relation, but below 6 µm some differences begin to appear as an effect of the Tamm states confinement inside the disk : a discretization of the Tamm states appears for the 4-µm disk. Moreover, for the 2-µm disk, the discrete Tamm state is blueshifted by 4 nm due to the Tamm state confinement.

Figure 3 shows the corresponding λ–θ emission patterns, simulated by finite-elements method (let us note that, for calculation times reasons, we in fact simulate y-translation-invariant structures, which is different from disk structures but yields qualitatively relevant interpretation). For a 20-µm disk, the emission pattern is similar to the simulated and experimental patterns for the 2D Tamm structure (again with a 25-nm shift between experiment and theory). As the disk diameter is decreased, a discretization of the Tamm states is observed. The spacing between discrete states increases as the disk diameter decreases due to Tamm states confinement. The quality factor of the experimental structure is lower than simulated because of fabrication imperfections, so that the Tamm-states discretization cannot be distinguished experimentally for the 10 and 8 µm disks although

confinement discretization appears clearly on the simulations. The higher-order confined Tamm states, which are distinct on the simulated patterns, also cannot be observed on the experimental data.

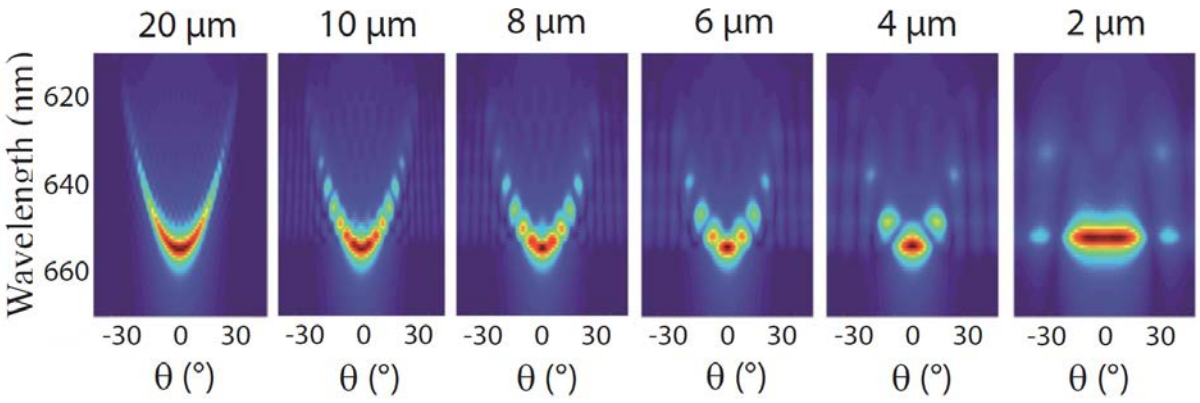

Figure 3. Emission spectrum for different emission angles, simulated for the same structure parameters as on fig 1 and various Ag diameters, for a structure invariant by translation, for emitters located at the position of the nanocrystals located at the disk centre (calculations performed using COMSOL Multiphysics).

CONCLUSION

We discussed here the theoretical and experimental properties of confined Tamm states in the visible domain, obtained between a SiO_2/TiO_2 Bragg mirror and a Ag disk. When including fluorescent colloidal nanocrystals in the last SiO_2 layer, the fluorescence spectra show a good coupling of the fluorophores to the Tamm states, and the confinement of the Tamm state below the disk is demonstrated by a discretization of the Tamm states and a blueshift of the emission peak with decreasing disk diameter. This behaviour is qualitatively well described by our numerical simulations, which show the field distribution corresponding to the various confined Tamm states. Future work will analyse the emission pattern depending on the detection and excitation positions.

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