Tamm plasmon-based cavity with a quasicrystalline type structuration

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Abstract. We have theoretically investigated Tamm plasmon structure covered by a quasicrystal symmetry subwavelength grating. We show that such structures can support plenty of high-Q hybrid optical eigenstates. The structure consists of a GaAs/Al$_{0.95}$Ga$_{0.05}$As Bragg reflector covered with a subwavelength Fibonacci silver/resist sequence. For the $F_5$ type coverage, two different operation regimes controlled by filling factor value were shown. We demonstrate the anti-crossing behaviour of these states spectral position. The considered system can be useful to enhance the emission of broadband light-emitting materials such as organic dyes and small molecules.

1. Introduction

In recent years, there is a growing interest of researchers in nanophotonic systems which support Tamm plasmon modes [1, 2]. Tamm plasmon (TP) is an electromagnetic state localized at the interface between the metal and the specially designed Bragg mirror. Tamm plasmon provides new possibilities for utilizing metallic parts in modern optoelectronic devices. Tamm plasmon based systems demonstrate lower absorption losses than systems with conventional surface plasmon modes [3]. For further progress in TP-based systems operation, losses need to be diminished. One of the approaches to reduce losses and increase control over the emission is a formation of the subwavelength elements out of the metallic layer [4, 5]. Besides the usual one-period grating, using different types of metallic photonic crystals [6, 7, 8] and photonic quasicrystal structures [9, 10] as a covering pattern is a promising way. Properties of these type systems such as negative refractive index, high-order symmetry and fractal density of photonic states can significantly increase light localization and open new application aspects of hybrid TP systems.

This paper is aimed at the further theoretical analysis of the TP mode tuning and emission control. We consider another type of subwavelength covering - multiperiodic metallic quasicrystal symmetry elements.

2. Results and discussion

We investigate a Tamm plasmon structure with an optical Fibonacci based subwavelength structuration of the covering silver layer (figure 1). The model structure consists of 30 pair GaAs/Al$_{0.95}$Ga$_{0.05}$As $\lambda/4$ layers distributed Bragg reflector (DBR) with a GaAs layer on the top and subwavelength grating formed by the metal and the resist material. The thickness of
the metal layer (silver) is 45 nm, and the thickness of the resist material layer (PMMA material) is 90 nm. The scheme of the TP structure with a periodic metal/resist grating is demonstrated in figure 1(a). Lateral period of the grating \( (d_M + d_R) \) is fixed as 250 nm. In a recent study [5], it was experimentally demonstrated, that variation of the filling factor parameter (degree of structures surface filling with metal elements) allow to move resonant wavelength and increase the quality factor of the TP in such systems. We will compare the properties of the TP cavity with periodic structuration with a quasicrystal (Fibonacci sequence based) covering.

**Table 1.** Examples of the first six Fibonacci sequences.

| Order | Configuration |
|-------|---------------|
| \( F_0 \) | \( M \) |
| \( F_1 \) | \( R \) |
| \( F_2 \) | \( MR \) |
| \( F_3 \) | \( RMR \) |
| \( F_4 \) | \( MRRMR \) |
| \( F_5 \) | \( RMRRMRRMR \) |
| \( F_6 \) | \( MRRMRRMRMRRMR \) |

**Figure 1.** (a) Scheme of the TP structure with the periodic sub-wavelength grating. (b) Scheme of the TP structure with the sub-wavelength grating formed by the Fibonacci optical lattice sequence.

The Fibonacci structure of the \( F_i \) order is constructed using the recurrent rule \( F_{i+1} = \{ F_{i-1}, F_i \} \) with initial values \( F_0 = M \) (single metallic layer) and \( F_1 = R \) (single resist and metal layer). Examples of the first six Fibonacci sequences are demonstrated in table 1 (sequences considered in the study are highlighted in bold). The scheme of the TP structure with the Fibonacci sequence based metal/resist grating is demonstrated in figure 1(b). Due to the fractal density of photonic states in the optical Fibonacci lattices [10], increasing order of the lattice can lead to more explicit features in the eigenmode spectrum. Therefore, we are analyzing how the order of the grating sequence \( (F_4, F_5, F_6) \) with same filling factors (ff) influence on the properties of TP mode: the resonance frequency position and the quality factor (Q factor).
Two-dimensional electromagnetic simulations were carried out using a finite element method (FEM). Periodic boundary conditions in the lateral dimension were used for all considered structures. Real and imaginary parts of a silver refractive index were obtained by fitting the experimental data. Reflectivity spectra were calculated for each structure with different filling factor in case of TE polarized wave and normal incidence. From the obtained spectra, we estimate the resonant wavelength and the Q factor of the TP and other hybrid eigenstates by fitting the spectrum dip using the Lorentz function.

Figure 2. Results of reflectivity spectra fitting: eigenstates spectral position and Q factor for $F_3$ (a), $F_5$ (b) and $F_6$ (c) covering quasicrystalline sequences. The blue line shows a dependence of resonant wavelength on the filling factor for TP structure with a periodical grating.

Figure 2 demonstrates the calculation results. Colour circles show eigenstates spectral position, colour and size show the value of Q factor. The blue line at each figure demonstrates the spectral position of the TP mode depending on the filling factor for the periodical structuration case. The results for TP cavity with the $F_4$ type structuration (fig. 2 (a)) don’t significantly differ from periodical lattice case. This coverage can be represented as two-period system with periods $P_1 = d_M + d_R$ and $P_2 = 2 \cdot d_M + d_R$. Quality factors of TP states have a maximum at filling factors less than 30% as in periodical lattice case. There are only a few differences: TP spectral position slightly shifted to higher energies area ($\approx 10nm$), a few low-Q eigenstates appear, at ff higher than 60% mode splits into several branches. In the $F_5$, $F_6$ cases the picture is more complicated. For the $F_5$ type coverage (fig. 2 (a)) there are two different operation modes, controlled by the filling factor parameter. For high ff values ($> 50\%$) there is only
one TP mode with spectral position and Q factor (less than 1000) very close to the periodic grating case. On the other hand, with low ff parameter value (< 50%) a number of high-Q hybrid eigenstates appears and strongly interact with the TP state. When the ff parameter is low, the complex diffraction properties in lateral direction takes place. In combination with the self-similar properties of the photonic quasicrystal sequence resonant properties of the system completely change which can lead to localized states. The peculiar behaviour of hybrid states spectral position is illustrated in details in fig.3. Figure 3 shows the calculated reflectivity spectrum distribution for the $F_5$ type structuration. Black dash lines show the spectral position of the three closest to TP spectral position states. In the red circle’s area, the anti-crossing behaviour can be seen.

When the order of the sequence increases ($F_6$ case), the number of appearing eigenstates increases too. In this case, for all filling factor values, there are many eigenstates, and it’s more complicated to highlight certain branches of modes because their positions are scattered more randomly than in the $F_5$ case. Nevertheless, in all considered Fibonacci coverage types there is a similar trend to periodic structuration - the most high-Q values appear in structures, defined by the ff parameter less than 40%.

3. Conclusions
Theoretical analysis of the subwavelength structuration with a quasicrystal symmetry influence on the properties of Tamm plasmon structure formed by GaAs/Al$_{0.95}$Ga$_{0.05}$As DBR with the silver metal coating layer on the top was provided. FEM method electromagnetic simulations were carried out with varying filling factor parameter for different orders of the Fibonacci based coverage structure ($F_4$, $F_5$, $F_6$). We have demonstrated that in TP structure with subwavelength structuration with quasicrystal based elements with the $F_5$ sequence or more a number of high-Q (more than 1000) modes support. Also, in the $F_3$ type coverage case two different regimes, controlled by filling factor value and peculiar behaviour of the eigenstates spectral position.

![Figure 3](image_url)

Figure 3. Reflectivity spectrum distribution of the TP cavity with $F_5$ sequence structuration. Black dashed lines show the dependence of the eigenstates spectral position on the filling factor. Red circles show anti-crossing areas. A vertical yellow dash-dot line at ff=50% separates areas correspond to two different regimes.
(modes anti-crossing) were demonstrated. The considered system can be useful to enhance the emission of broadband light-emitting materials such as organic dyes and small molecules.

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