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Characteristics of local density of optical states in a tapered grated waveguide at resonant states

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ABSTRACT

Based on Green's function method, we have conducted a systematic numerical investigation on the characteristics of local density of optical states of a tapered grated waveguide and other related parameters such as field profiles, transmission and scattering loss at left and right resonant states. The tapered grated sections are additional corrugated sections at both edges of a regular grated waveguide. We consider two different variations of the corresponding sections namely the uniform and non-uniform corrugation depth configurations. It is found that the characteristics of the local density of optical states for both variations at resonant states are different, especially for the left resonant state. In the mean time, compared to the other cases, a relatively distinct characteristic is also found on the transmission and scattering loss parameters of uniform variations at right resonant case.

1. Introduction

In integrated optical devices for sensor applications, a specific structure i.e. a grated waveguide (GWg) in the form of an asymmetric corrugated slab waveguide has been intensively used by utilizing the existence of photonic band gap (PBG) in its transmission characteristics, where light in certain range of wavelength cannot be propagated [1]. For the corresponding applications, wavelength variations of the resonant states of PBG edges are usually considered as a platform for sensing the refractive index changes of surrounding environment [2].

In its implementation, the associated resonant states does not always allow good sensitivity of the device due to photon scattering that lead to the loss of energy. This loss of energy is responsible for the decreasing of optical sensor device sensitivity in general [3]. Recently, it was reported that the modification of GWg structure namely by introducing tapered grated sections with varying corrugation depths at the edges of the corresponding GWg could led to the loss reduction and transmission enhancement [4]. It was shown that for a specific GWg structure, the modification could reduced loss up to 85% and increased transmission up to 15%. However, this modification could also led to the reduction of group velocity, which in turn, led to the reduction of sensitivity itself. Nevertheless, the effect of this group velocity reduction on the decrease of device sensitivity is relatively insignificant compare to the effect of the resulted loss reduction on sensitivity enhancement.

In the mean time, it is well known that one of the important properties of an optical structure is its availability to accomodate photon eigenmodes at specific location inside an optical structure [5]. This property is represented by the so called local density of optical states or LDOS. There are several ways to calculate LDOS e.g. [6–12], one of them is by means of Green's function method in the form of Dyson's formulation [11]. In this method the corresponding LDOS can be calculated directly without calculating the electromagnetic field first as needed in the method given in, for instance, Ref. [6].

Following Ref. [4], in this report we discuss the characteristics of LDOS of the associated GWg structure with respect to the structural variations of tapered grated sections. Similar to that reference, we also employ the same Green's function method to calculate the related LDOS. To the best of our knowledge, the discussion regarding the characteristics of LDOS in the corresponding structure has never been reported elsewhere.

We organize the discussion as follows: in Section 2 we discuss the corresponding waveguide structure, while formulation of the Green's function method and definition of the LDOS are given in Section 3. The results of our investigation regarding the characteristics of LDOS for different variations of tapered grated sections are discussed in Section 4. We end this report with a summary in

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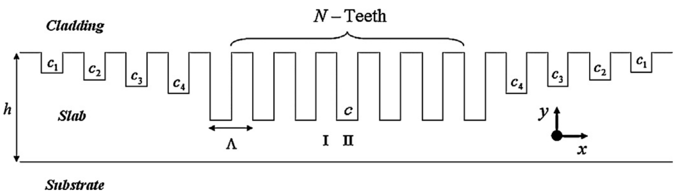

Fig. 1. Illustration of grated waveguide with additional tapered grated sections. The illuminated TE-Mode is linearly polarized in z-direction.

Section 5. It should be pointed out that in this report we present many figures to give more visual explanations on our results.

2. Tapered grated waveguide structure

We consider a three layer GWg system consisting of a semi-infinite air cladding with a slab $n_{clad} = 1$, dielectric waveguide of $d = 160$ nm thickness, incorporated with a finite length corrugated section in the upper side and $n_{slab} = 1.98$, and a semi-infinite substrate of $n_{sub} = 1.44$. At both edges of the main GWg section, we insert additional grated sections with tapered corrugation depths as shown in Fig. 1, which is the same to a structure that was discussed in Ref. [4]. The number of teeth in the main grating section is denoted by N with depth c, such that there are $N + 2$ corrugations. The period is set to $\Lambda = 200$ nm. In each additional grated section, the number of corrugations is set to four with each depth is denoted by c_1, c_2, c_3 and c_4.

We assume that the slab waveguide is illuminated by an electromagnetic field in TE fundamental mode from the left side. In general, due to the finite corrugated section length it is obvious that the field is also experiencing scattering phenomenon that leads to the loss of energy, which can cause disadvantage to the sensing performance.

3. Green's function method and definition of LDOS

In principle, to solve numerically the Maxwell equation of TE mode propagation, one can use several methods such as finite difference method, finite element method [1] and Green's function method [11,12]. Among those methods, the Green's function method has, at least, three advantages compared to other methods. In contrast to the finite difference and finite element method, for example, this method does not need any boundary conditions such that it can be implemented in a relatively small computational window [4]. Other advantages are its ability to calculate the LDOS quantity directly based on Dyson's formulation and its easiness to handle small perturbation on the considered structure. Based on these advantages, we choose to use this method for calculating the corresponding LDOS of the tapered GWg. However, it should be noted that the disadvantage of this method is its requirement on large memory and time consumption.

Taking advantage that the Green's function is a scalar function $G(r, r')$ for TE mode, such that in order to find the related function in the Dyson's formulation for a specific optical structure one only has to solve the following integral equation [10]:

$$G\left(r, r'\right) = G^B\left(r, r'\right) + \int_{\Omega} G^B\left(r, r''\right) k_0^2 \Delta\varepsilon\left(r''\right) G\left(r'', r'\right) \mathrm{d}\Omega'' \qquad (1)$$

here $G^B(r, r')$ is the Green's function of the background structure and in our case is the aforementioned three layer systems. The symbols $r = (x, y)$, $r' = (x', y')$ and k_0 denote the observation point, electric dipole position, and vacuum wavenumber, respectively, while $\Delta\varepsilon$ represents the permittivity contrast between the background structure and the considered GWg structure. The area of computational window is denoted by Ω.

Table 1
Variation of additional tapered grated sections with uniform corrugation depth. The symbols R12 and R20 represent the regular structure with $N = 12$ and $N = 20$, respectively.

Variations	c_1 (nm)	c_2 (nm)	c_3 (nm)	c_4 (nm)
R12	0	0	0	0
U1	20	20	20	20
U2	40	40	40	40
U3	60	60	60	60
U4	80	80	80	80
R20	100	100	100	100

To solve Eq. (1) numerically, we can use the following discretization scheme [11,12]:

$$G_{ij} = G_{ij}^B + \sum_{\substack{i=1, j=1 \\ i \neq k, j \neq k}}^{P} G_{ik}^B k_0^2 \Delta\varepsilon_k \Delta\Omega_k G_{kj} + M_i k_0^2 \Delta\varepsilon_i G_{ij} - L\frac{\Delta\varepsilon_i}{\varepsilon_B} G_{ij} \qquad (2)$$

where P is the number of mesh grids, ε_B is the background permittivity. The parameters M and L are introduced to handle singularity in Eq. (1) [11]. The discrete Eq. (2) can be solved iteratively using an algorithm introduced in Ref. [10], namely by adding the perturbation one-by-one into the background structure until the desired GWg structure formed.

From the calculated Green's function, one can easily construct the field profile simply by solving the following discrete equation [12]:

$$E_i = E_i^B + \sum_{\substack{i=1, j=1 \\ i \neq j}}^{P} G_{ij} k_0^2 \Delta\varepsilon_j E_j^B \Delta\Omega_j + M_i k_0^2 \Delta\varepsilon_i E_i - L\frac{\Delta\varepsilon_i}{\varepsilon_B} E_i \qquad (3)$$

where E^B is the fundamental TE mode of the background i.e. the three layer systems. In the mean time, also from Eq. (2), one can calculate the LDOS by using the following dimensionless definition [10]:

$$\rho(r) = \frac{Im\left[G(r, r)\right]}{Im\left[G^B(r, r)\right]} \qquad (4)$$

here ρ is a normalized LDOS at specific position r which can be used to describe the density of electric field eigenmodes in the range between λ and $\lambda + d\lambda$, where λ is the related wavelength [5,8].

As previously pointed out, the calculation of Eq. (2) requires a relatively large computer memory allocation. Nevertheless, this problem can be overcome by choosing as small as possible computational window. Here, to conduct the numerical calculation for LDOS and field profile based on Eqs. (2) and (3), respectively, the related computational window is defined as follows: $(x_l, x_r) = (0, 8)$ μm and $(y_b, y_t) = (-0.04, 0.2)$ μm, where $x_{l(r)}$ denotes the left (right) boundary in x-direction, while $y_{b(t)}$ denotes the bottom (top) boundary in y-direction. The mesh size is set to $(\Delta x, \Delta y) = (0.02, 0.01)$ μm.

4. Characteristics of LDOS at resonant states

To characterize the LDOS at left and right resonant states with shorter and longer wavelengths, on the related photonic band gap, respectively, we consider for the additional tapered grated sections, as shown in Fig. 1, several variations. The corresponding variations are classified into two categories namely uniform and non-uniform corrugation depths as given in Tables 1 and 2, respectively. It is important to note that those variations are varied between two regular GWg with $N = 12$ and $N = 20$. Here, we set $c = 100$ nm.