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Time-reversed lasing based on one-dimensional gratings

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ABSTRACT

We show that a one-dimensional grating can generally exhibit time-reversed lasing better than a uniform slab. As the effective refractive index of a grating can be controlled by adjusting the geometric parameters, the time-reversed lasing can be realized for any incident wavelength in it. Moreover, the operating frequency range of coherently perfect absorption for a grating structure is remarkably broad compared with a uniform structure. All these behaviors are demonstrated with GaAs/Air gratings illuminated around 794.8 nm. The properties of the proposed grating imply the potential applications such as detectors, transducers, and broad band absorber.

1. Introduction

It has been recently demonstrated that the time-reversed process of lasing can be feasibly realized in resonators consisting of media with particular degree dissipation, which leads to incident radiation perfectly absorbed [1,2]. Such resonator systems, termed "coherent perfect absorbers (CPAs)", attract much attention at present due to the widely potential applications such as modulators, detectors, and phase controlled optical switches [3–6]. Actually, the possibility of time-reversed process of lasing had been briefly mentioned in early laser studies [7,8], but detailed theory investigation and experimental realization only began with the recent work of Chong et al. [1], in which the physical picture of time-reversed lasing and specific two-channel CPA were well illustrated in uniform slab geometry. More recently, the two-channel CPA in Si (silicon) slab was experimentally demonstrated by Wan et al. [2]. In this Letter, possible CPA for any incident wavelength is considered, and a one-dimensional grating [9,10] is proposed instead of the uniform slab for realizing time-reversed lasing. We show that the grating structure can exhibit time-reversed lasing like uniform slab and can even do for any incident wavelength by choosing proper grating geometric parameters. Moreover, compared with uniform slab, significant absorption can be achieved in a broad frequency range for this grating structure.

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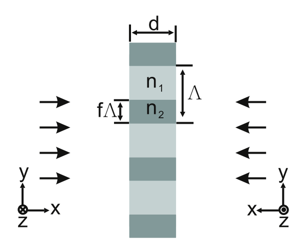

Fig. 1. (Color online.) Schematic of proposed grating structure consisting of alternating layers with refractive indices n_1 and n_2, where Λ and d are severally the period and thickness, and f is the filling factor of dielectric n_2.

2. Time-reversed lasing

The schematic of the proposed structure is shown in Fig. 1, which consists of alternating dielectric layers with refractive indices n_1 and n_2. The geometric parameters characterizing this structure are period Λ, grating thickness d, and filling factor f, which is the ratio of the thickness of layer n_2 to the period. As is well known, when Λ is much smaller than the wavelength of incident light λ, the grating can be treated as a uniform slab with effective refractive index n_{eff}, which can be evaluated with the effective medium theory (EMT) [11–13]. Here, we consider normal incidence of TE polarization light on the grating, then its effective refractive index n_{eff} is described by the EMT in the second-order approximation as

$$n_{\text{eff}} = \sqrt{(1-f)n_1^2 + f n_2^2 + \frac{\pi^2}{3}\left(\frac{\Lambda}{\lambda}\right)^2 f^2(1-f)^2\left(n_2^2-n_1^2\right)^2}. \quad (1)$$

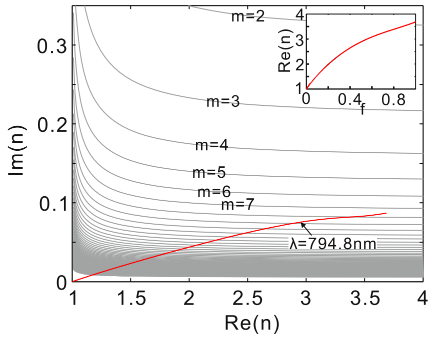

Fig. 2. (Color online.) Relations of Im(n) and Re(n). Gray solid curves represent the relations deduced from Eq. (3) and denote CPA zeros for a m range from 2 to 107. Red solid curve represents the trajectory of n_{eff} of grating for 794.8 nm as f varies from 0 to 1. Inset: dependence of Re(n) of n_{eff} on f for 794.8 nm.

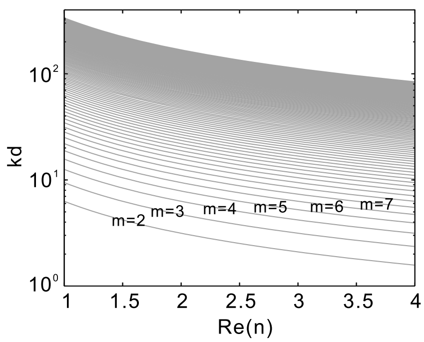

Fig. 3. Relations of kd and Re(n) for practical realization of time-reversed lasing. The relations are deduced from Eq. (2) and m ranges from 2 to 107.

As seen in Eq. (1), the real part n_{Re} and imaginary part n_I of n_{eff} for a grating is a function of the filling factor f. When f grows from 0 to 1, n_{eff} varies from the value of n_1 to that of n_2. Consequently, n_I is related to n_{Re} through f.

Before we analyze time-reversed lasing in the grating structure, we first review the two-channel CPA condition for a uniform slab, which was discussed in Ref. [1]. For a uniform slab with refractive index $n = n_{Re} + in_I$ ($n_{Re} > 1$, $n_I > 0$) and thickness d surrounded by dielectric with refractive index n_0, the CPA condition of having a zero eigenvalue is that $e^{inkd} = \pm(n - n_0)/(n + n_0)$, where k is the wave number in vacuum. Assuming that $n_I \ll n_{Re}$, the CPA zero solution of this equation is approximately

$$n_{Re,m} \approx m\pi/(kd) \quad (m = 1, 2, 3, \ldots), \tag{2}$$

and $n_{I,m} \approx 1/(kd)\ln[(n_{Re,m} + n_0)/(n_{Re,m} - n_0)]$. From this solution we further deduce the relation between n_{Re} and n_I as

$$\frac{n_{I,m}}{n_{Re,m}} = \frac{\ln[(n_{Re,m} + n_0)/(n_{Re,m} - n_0)]}{m\pi} \quad (m = 1, 2, 3, \ldots). \tag{3}$$

The realization of time-reversed lasing requires that the parameters k, n_{Re}, n_I, and d must together satisfy the relations (2) and (3) referred to as the CPA condition. In other words, to enable time-reversed lasing in a structure, the following two conditions must be satisfied: one is that the refractive index n (i.e., the effective refractive index n_{eff} in our structure) must be such a complex value that meets Eq. (3), the second is that the value of d must be properly chosen to meet Eq. (2). The first condition is a prerequisite, and it is displayed with gray solid curves in Fig. 2 for $n_0 = 1$, where a range of m from 2 to 107 is considered. The corresponding value of d calculated with Eq. (2) is plotted in Fig. 3. In general, the complex refractive index n of a uniform slab for a given incident wavelength is within the spacing between gray solid curves in Fig. 2 rather than falls on one of them.

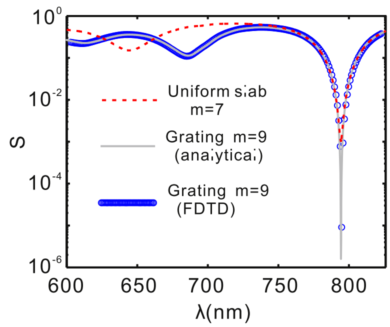

Fig. 4. (Color online.) Scattering S for uniform GaAs slab (gray solid curve) and GaAs/Air grating (red dashed curve) around 794.8 nm obtained from analytical method. For uniform GaAs slab, the thickness is $d = 0.7549$ μm, which matches with $m = 7$ and form CPA resonance at 794.8 nm. For grating structure, thickness $d = 1.2401$ μm with $m = 9$ form 794.8 nm resonance; here, n_{eff} at 794.8 nm is $2.8847 + 0.07379$i, which lies at the cross point of n_{eff} trajectory (Fig. 2, red solid curve) and CPA zeros curve of $m = 9$. Scattering S for GaAs/Air grating obtained by performing FDTD is depicted with blue circle curve.

Typically, the scattered intensity of a uniform slab near a CPA zero is $I \sim c_0|n - n_{CPA,m}|^2$, where c_0 is of order unity [1] and $n_{CPA,m} = n_{Re,m} + in_{I,m}$. To reduce the scattered intensity as largely as possible, one should make $n_{Re,m} \approx n_{Re}$ by choosing the value of kd according to Eq. (2), since $n_I \ll n_{Re}$ in general. In this situation, the value of $|n - n_{CPA,m}|$ is dominated by the difference between n_I and $n_{I,m}$, i.e., $|n - n_{CPA,m}| \approx |n_I - n_{I,m}|$. Note that for different m, the value of kd chosen is different [see Eq. (2)] and so is the result of $|n_I - n_{I,m}|$. Evidently, there exists an optimal value of m, at which both of $|n_I - n_{I,m}|$ and $|n - n_{CPA,m}|$ reach their minimums. As seen from Fig. 2, when n_I is small and n is located in the region with CPA zero curves of large m, the difference $|n_I - n_{I,m}|$ could be very small and the scattered intensity extremely low, namely, significant CPA absorption could be achieved. But for widely used semiconductor materials in integrated photonics, n_I is often considerably large and n lies within the spacing between CPA zero curves with small m. Consequently, the difference $|n_I - n_{I,m}|$ is not small enough to ensure significant absorption. For our grating structure, both of the real and imaginary parts of the effective refractive index n_{eff} are adjustable, and if we set $n_1 = 1$, the values of (n_{Re}, n_I) can be tuned from $(1, 0)$ to $[\mathrm{Re}(n_2), \mathrm{Im}(n_2)]$. Obviously, small n_I is available for the grating structure. Moreover, n_{Re} and n_I vary continuously with the filling factor, as illustrated by the red solid line in Fig. 2, which represents a trajectory of n_{eff} as the filling factor varies from 0 to 1, thus for any incidence wavelength, there always exist a number of locations, at which the n_{eff} trajectory intersects the CPA zeros curves. From these cross points we can find an appropriate value of the filling factor to make that $|n_{eff} - n_{CPA,m}|^2 = 0$. So the grating structure is capable of exhibiting perfectly time-reversed lasing for a given wavelength.

We now consider an example that is GaAs/Air grating surrounded by air with $\Lambda = 141.5$ nm. The incident wavelength is assumed to be $\lambda = 794.8$ nm, at which the refractive index of GaAs is $n_2 = 3.685 + 0.087$i [14]. The trajectory of n_{eff} of this grating for $\lambda = 794.8$ nm is just the red solid curve in Fig. 2, and it intersects all gray curves with $m \geqslant 8$. In the inset of Fig. 2, the relation of n_{Re} and f is presented. As anti-symmetric CPA modes are considered here, the CPA zero curve closest to the point $n_2 = 3.685 + 0.087$i is the one with $m = 7$. Thus, for a uniform GaAs slab, we should choose a thickness of $d = 0.7549$ μm to make $n_{Re,7} = 3.685$ and then achieve resonance at 794.8 nm. For $d = 0.7549$ μm, the scattering coefficient S, defined as the ratio of the scattered and input intensities (around 794.8 nm), is plotted in Fig. 4 as red dashed curve. For our grating structure, we can make n_{eff} just being at the cross point of its trajectory (Fig. 2, red solid curve) and the CPA zero curve with a certain m, for example, the one with $m = 9$ and