The design of ultra-strong laser with one-dimensional function photonic crystal

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With the optical kerr effect, the conventional photonic crystal can be turned into the function photonic crystal under the action of pump light. In the paper, we have designed the ultra-strong light source and laser with one-dimensional function photonic crystal. When the incident light is the ordinary light, the output is ultra-strong light source, and when the incident light is the low power laser, the output is ultra-strong laser, the maximum magnification can be reached $10^{80}$ and even more. Otherwise, we analyzed the effect of period number, medium refractive index and thickness, incident angle, the pump light irradiation way and pump light intensity on the magnification, these results shall help to optimal design ultra-strong light source and laser.

PACS: 42.70.Qs, 78.20.Ci, 42.60.Da
Keywords: photonic crystal; ultra-strong light source; ultra-strong laser; laser intensity; magnification

1. Introduction

Photonic crystals (PC) are a new kind of materials which facilitate the control of the light [1-5]. An important feature of the photonic crystals is that there are allowed and forbidden ranges of frequencies at which light propagates in the direction of index periodicity [6-8]. Due to the forbidden frequency range, known as photonic band gap (PBG) [9-12], which forbids the radiation propagation in a specific range of frequencies. The existence of PBGs will lead to many interesting phenomena, e.g., modification of spontaneous emission [13-15] and photon localization [16-18]. Thus numerous applications of photonic crystal have been proposed in improving the performance of optoelectronic and microwave devices such as high-efficiency semiconductor lasers, light emitting diodes, wave guides, optical filters, high-Q resonators, antennas, frequency-selective surface, optical limiters and amplifiers [19-21]. These applications would be significantly enhanced if the band structure of the photonic crystal could be tuned.

In Refs. [22-25], we have proposed the one-dimensional function photonic crystal, which is constituted by two media $A$ and $B$, their refractive indices are the functions of space position. Unlike conventional photonic crystal (PCs), which is constituted by the constant refractive indices media $A$ and $B$. We have studied the transmissivity and the electric field distribution with and without defect layer, and have designed some optical devices, such as optical amplifier, attenuator, optical diode and optical triode by the function photonic crystal.

In the paper, we have designed the ultra-strong light source and laser with one-dimensional function photonic crystal. When the incident light is the ordinary light, the output is ultra-strong light source, and when the incident light is the low power laser, the output is ultra-strong laser, the maximum magnification can be reached $10^{80}$ and even more. Otherwise, we analyzed the effect of period number, medium refractive index and thickness, incident angle, the pump light irradiation way and pump light intensity on the magnification, these results shall help to optimal design ultra-strong light source and laser.

2. The transmissivity of one-dimensional function photonic crystal

In Refs. [22-25], we have given the one-dimensional function photonic crystal transfer matrices $M_B$ and

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\( M_A \) of the media \( B \) and \( A \) for the TE wave, they are

\[
M_B = \begin{pmatrix}
\cos \delta_b & -i \sin \delta_b \\
-in_b(0) \sqrt{\frac{2 \mu_0}{\varepsilon_0}} \cos \theta^l_I \sin \delta_b & \sqrt{\frac{2 \mu_0}{\varepsilon_0}} n_b(b) \cos \theta^l_I
\end{pmatrix},
\]

\[
\begin{pmatrix}
\cos \delta_a \\
-in_a(0) \sqrt{\frac{2 \mu_0}{\varepsilon_0}} \cos \theta^l_I \sin \delta_a & \sqrt{\frac{2 \mu_0}{\varepsilon_0}} n_a(a) \cos \theta^l_I
\end{pmatrix},
\]

where

\[
\delta_b = \omega c n_b(b) \cos \theta^l_I \cdot b, \quad \delta_a = \omega c n_a(a) \cos \theta^l_I \cdot a,
\]

\[
\cos \theta^l_I = \sqrt{1 - \frac{n_b^2}{n_b^2(b)} \sin^2 \theta^0}, \quad \cos \theta^l_I = \sqrt{1 - \frac{n_a^2}{n_a^2(a)} \sin^2 \theta^0},
\]

and

\[
\cos \theta^{II}_I = \sqrt{1 - \frac{n_b^2}{n_b^2(b)} \sin^2 \theta^0}, \quad \cos \theta^{II}_I = \sqrt{1 - \frac{n_a^2}{n_a^2(a)} \sin^2 \theta^0}.
\]

In one period, the transfer matrix \( M \) is

\[
M = M_B \cdot M_A
\]

\[
\begin{pmatrix}
\cos \delta_b & -i \sin \delta_b \\
-in_b(0) \sqrt{\frac{2 \mu_0}{\varepsilon_0}} \cos \theta^l_I \sin \delta_b & \sqrt{\frac{2 \mu_0}{\varepsilon_0}} n_b(b) \cos \theta^l_I
\end{pmatrix},
\]

\[
\begin{pmatrix}
\cos \delta_a \\
-in_a(0) \sqrt{\frac{2 \mu_0}{\varepsilon_0}} \cos \theta^{II}_I \sin \delta_a & \sqrt{\frac{2 \mu_0}{\varepsilon_0}} n_a(a) \cos \theta^{II}_I
\end{pmatrix}.
\]

Where \( n_b(0), n_b(b), n_a(0) \) and \( n_a(a) \) are the starting point and endpoint values of refractive indices for the media \( B \) and \( A \), \( b \) and \( a \) are the thickness of media \( B \) and \( A \), \( \theta^0 \) is incident angle, \( n_0 \) is air refractive index.

For the one-dimensional function photonic crystal of structure \((BA)^N\), its characteristic equation is

\[
\begin{pmatrix}
E_1 \\
H_1
\end{pmatrix} = M_B M_A M_B M_A \cdots M_B M_A \begin{pmatrix} E_{N+1} \\
H_{N+1}
\end{pmatrix}
\]

\[
= M \begin{pmatrix} E_{N+1} \\
H_{N+1}
\end{pmatrix} = \begin{pmatrix} A & B \\
C & D
\end{pmatrix} \begin{pmatrix} E_{N+1} \\
H_{N+1}
\end{pmatrix},
\]

with the total transfer matrix \( M \), we can obtain the transmission coefficient \( t \), it is

\[
t = \frac{E_{N+1}}{E_{in}} = \frac{E_{out}}{E_{in}} = \frac{2 \eta_0}{A \eta_0 + B \eta_0 \eta_{N+1} + C + D \eta_{N+1}},
\]

and the magnification \( \beta \) of ultra-strong light source and laser \( \beta \) are defined as

\[
\beta = |t| = \left| \frac{E_{out}}{E_{in}} \right| = \left| \frac{2 \eta_0}{A \eta_0 + B \eta_0 \eta_{N+1} + C + D \eta_{N+1}} \right|.
\]
FIG. 1: The pump light vertically irradiate one-dimensional photonic crystal, the media $B$ and $A$ are respectively irradiated by the same pump light.

FIG. 2: The pump light vertically irradiate one-dimensional photonic crystal, and every one-period $(BA)$ is respectively irradiated by the same pump light.

Where $E_1 = E_{in} + E_r$, $E_{in}$ is the incident electric field, $E_r$ is the reflected electric field, $E_{N+1} = E_{out}$ is the output electric field and $\eta_0 = \eta_{N+1} = \sqrt{\frac{c}{\varepsilon_0}} \cos \theta^0$.

3. The design principle of ultra-strong light source and laser

In the following, we shall explain how to turn the one-dimensional conventional photonic crystal into the one-dimensional function photonic crystal, and give the design principle of the ultra-strong light source and laser. In nonlinear optics, the medium refractive index is the linear function of light intensity $I$, which is called the optical kerr effect, it is [26]

$$n(I) = n_0 + n_2 I,$$ (10)

where $n_0$ represents the usual, weak-field refractive index, the optical Kerr coefficient $n_2 = \frac{3}{4} n_0^2 \chi^{(3)}$, and $\chi^{(3)}$ is the third-order nonlinear optical susceptibility.

In Fig. 1, the pump light vertically irradiate one-dimensional photonic crystal, the media $B$ and $A$ are respectively irradiated by the same pump light, and the pump light intensity distribution $I$ is the function of space position $x$, it is

$$I = I_0 x,$$ (11)

substituting Eq. (11) into (10), there is

$$n(x) = n_0 + n_2 I_0 x,$$ (12)
where \( I_0 \) is the intensity coefficient of pump light. By the the optical kerr effect, the conventional medium refractive index \( n_0 \) become the linear function \( n(x) \) of space position \( x \), i.e., the refractive indices \( n_b \) and \( n_a \) of conventional media \( B \) and \( A \) should be become the linear functions \( n_b(x) \) and \( n_a(x) \) by the pump light.

With Eq. (12), the refractive indices starting point and endpoint values of media \( B \) and \( A \) can be written as:

\[
\begin{align*}
n_b(0) &= n_b, & n_b(b) &= n_b + n_{2b}I_0b, \\
n_a(0) &= n_a, & n_a(a) &= n_a + n_{2a}I_0a,
\end{align*}
\]  

(13)

(14)

In Fig. 2, the pump light vertically irradiate one-dimensional photonic crystal, and every one-period \((BA)\) is respectively irradiated by the same pump light. In every one-period \((BA)\), the refractive indices starting point and endpoint values of media \( B \) and \( A \) are

\[
\begin{align*}
n_b(0) &= n_b, & n_b(b) &= n_b + n_{2b}I_0b, \\
n_a(0) &= n_a + n_{2a}I_0b, & n_a(a) &= n_a + n_{2a}I_0(a + b),
\end{align*}
\]  

(15)

(16)

where \( n_b(n_a) \) is the refractive index of conventional medium \( B(A) \) (without joining pump light), \( n_b(0)(n_a(0)) \), \( n_b(b)(n_a(a)) \) are the refractive indices starting point and endpoint values of medium \( B(A) \) (with joining pump light), \( b(a) \) is the thickness of medium \( B(A) \), and \( n_{2b}(n_{2a}) \) is the optical Kerr coefficient of medium \( B(A) \).

4. Numerical result

In this section, we shall calculate the magnification \( \beta \) of the ultra-strong light source and laser designed by the one-dimensional function photonic crystal. The main parameters are: The conventional media \( B \) and \( A \) (without joining pump light) refractive indices \( n_b = 1.47, n_a = 1.58 \), thickness \( b = \frac{\lambda a}{n_b}, a = \frac{\lambda b}{n_a} \), the optical Kerr coefficient \( n_{2b} = 2.0 \times 10^{-6}, n_{2a} = 2.3 \times 10^{-6} \), the intensity coefficient of pump light \( I_0 = 5.0 \times 10^{10}(W/cm) \), the central wavelength incident \( \lambda_0 = 1.55 \times 10^{-6}m \), the incident angle \( \theta_i^0 = 0 \), the one-dimensional function photonic crystal structure is \((BA)^N\), where \( N \) is the periodic number. Firstly, we shall calculate the ultra-strong light source and laser magnification \( \beta \) under the pump light action of Fig. 1. In Fig. 1, the pump light vertically irradiate one-dimensional photonic crystal, the media \( B \) and \( A \) are respectively irradiated by the same pump light. Substituting Eqs. (13) and (14) into (6), we can obtain the transfer matrix \( M \) of one period. With Eqs. (7), (8) and (9), we can calculate the magnification \( \beta \), they are shown in Figs. 3-11, which give the relation between magnification \( \beta \) and incident light frequency \( \omega \). In Fig. 3, the period number \( N = 32 \), the maximum magnification \( \beta_{max} = 1.8 \times 10^{14} \). In Fig. 4, the period number \( N = 82 \), the maximum magnification \( \beta_{max} = 3.4 \times 10^{36} \). In Fig. 5, the period number \( N = 162 \), the maximum magnification \( \beta_{max} = 1.5 \times 10^{72} \). From Fig. 3 to Fig. 5, we can find the maximum magnification \( \beta_{max} \) increases with the period number \( N \) increasing. In Fig. 6, the intensity coefficient \( I_0 \) of pump light is \( I_0 = 2.0 \times 10^{10}(W/cm) \), other parameters are the same as In Fig. 5, the maximum magnification \( \beta_{max} = 9.6 \times 10^{37} \), i.e., the intensity coefficient \( I_0 \) of pump light decreases, the maximum magnification \( \beta_{max} \) reduces. In Fig. 7, the medium thickness \( b = 1.6 \times 10^{-6} \), other parameters are the same as In Fig. 5, the maximum magnification \( \beta_{max} = 4.2 \times 10^{37} \), i.e., the medium thickness increases, the maximum magnification \( \beta_{max} \) increases. In Fig. 8, the medium \( B \) refractive index \( n_b = 1.27 \), other parameters are the same as In Fig. 5, the maximum magnification \( \beta_{max} = 1.3 \times 10^{39} \), i.e., the medium refractive index decreases, the maximum magnification \( \beta_{max} \) reduces. In Fig. 9, the medium \( B \) optical Kerr coefficient \( n_{2b} = 1.6 \times 10^{-6} \), other parameters are the same as In Fig. 5, the maximum magnification \( \beta_{max} = 2.3 \times 10^{37} \), i.e., the optical Kerr coefficient decreases, the maximum magnification \( \beta_{max} \) reduces. In Figs. 10 and 11, the incident angle \( \theta_i^0 = \frac{\pi}{6} \) and \( \theta_i^0 = \frac{\pi}{7} \), other parameters are the same as In Fig. 5, the maximum magnification are \( \beta_{max} = 4.6 \times 10^{57} \) and \( \beta_{max} = 1.9 \times 10^{38} \), respectively, i.e., with the incident angle increasing, the maximum magnification \( \beta_{max} \) increases. Nextly, we shall calculate the ultra-strong light source and laser magnification \( \beta \) under the pump light action of Fig. 2. In the Fig. 2, the pump light vertically irradiate one-dimensional photonic crystal, and every one-period \((BA)\) is respectively irradiated by the same pump light. Substituting
Eqs. (15) and (16) into (6), we can obtain the transfer matrix $M$ of one period. With Eqs. (7), (8) and (9), we can calculate the magnification $\beta$, it is shown in Fig. 12. In Fig. 12, the all parameters are the same as In Fig. 5, the maximum magnification are $\beta_{\text{max}} = 6.8 \times 10^{42}$. Comparing Fig. 5 with Fig. 10, the maximum magnification $\beta_{\text{max}}$ is different for the different irradiation way of pump light (Figs. 1 and 2). Obviously, the irradiation way of Fig. 1 can obtain the more magnification. By computation above, we can find when the incident light is the ordinary light or low power laser, the output ultra-strong light source or laser can be produced by the one-dimensional function photonic crystal.

The reason of ultra-strong light amplification is the incident light absorb a lot of energy of pump light. We can compare the ultra-strong light amplifier with the electric current amplifier. The incident and output light fields are the equal of the input and output alternating electrical signals, and the pump light amount to direct-current power source.

5. Conclusion

In the paper, we have designed the ultra-strong light source and laser with one-dimensional function photonic crystal. When the incident light is the ordinary light, the output light is ultra-strong light source, and when the incident light is the low power laser, the output light is ultra-strong laser, the maximum magnification can be reached $10^{80}$ and even more. Otherwise, we found the maximum magnification should be increased when the period number, medium refractive index and thickness, incident angle and optical Kerr coefficient increase, the maximum magnification of Fig. 1 is larger than Fig. 2, these results shall help to optimal design ultra-strong light source and laser.

6. Acknowledgment

This work was supported by the Scientific and Technological Development Foundation of Jilin Province (no.20130101031JC).
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FIG. 3: The magnification of period number $N = 32$.

FIG. 4: The magnification of period number $N = 82$. 

FIG. 5: The magnification of period number $N = 162$.

FIG. 6: The magnification of period number $N = 162$ and the intensity coefficient $I_0 = 2.0 \times 10^{10}(W/cm)$. 
FIG. 7: The magnification of period number $N = 162$ and thickness $b = 1.6 \times \frac{\lambda}{\sin \theta}$.

FIG. 8: The magnification of period number is $N = 162$ and the refractive index $n_b = 1.27$. 
FIG. 9: The magnification of period number is $N = 162$ and the optical Kerr coefficient $n_{2b} = 1.6 \times 10^{-6}$.

FIG. 10: The magnification of period number $N = 162$, the incident angle $\theta = \frac{\pi}{6}$. 
FIG. 11: The magnification of period number $N = 162$, the incident angle $\theta = \frac{\pi}{3}$.

FIG. 12: The magnification of the all parameters are the same as in Fig. 5 and the pump light irradiate with Fig. 2.