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Localized modes in one-dimensional nonlinear periodic photonic structures

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Abstract
We study the generation of localized second-harmonic modes in a one-dimensional photonic crystal with a defect in the form of a phase slip. Due to the presence of the defect the photonic crystal has localized in-gap modes. We consider the case when the fundamental mode is localized in the first bandgap and because of its nonlinear properties it generates a localized second-harmonic mode. As a function of the parameters of the photonic crystal and the defect the intensity of the second-harmonic mode has sharp maxima, which correspond to the resonance condition, i.e. the frequency of the second-harmonic mode is equal to the frequency of the localized mode in the second bandgap. We find the conditions when such resonance can be achieved. We also determine the optimal parameters of the photonic crystal at which the generation of the second-harmonic mode becomes less sensitive to violation of the resonance condition.

1. Introduction

One of the applications of photonic crystals, i.e. periodic modulation of the dielectric constant, is related to the localization of light in the presence of defects within the bandgaps of the photonic crystal [1, 2]. In this case the localized modes of the photonic crystal become resonators with high quality factors [3]. Another important application of photonic crystals is related to the enhancement of nonlinear effects in periodic structures [4]. This enhancement gives the possibility of tailoring the photon dispersion relation in photonic crystals. This can result, for example, in the realization of a quasi-phase-matching condition for second-harmonic generation in photonic crystals [5–9]. Under quasi-phase-matching conditions a high-intensity second-harmonic mode can be generated in periodic photonic structures. Another method to enhance the generation of the second-harmonic mode is to incorporate the nonlinear media in a resonant cavity [10–14]. If the cavity has double resonance properties, i.e. both the fundamental mode and the second-harmonic mode are resonant modes of the cavity, then the fundamental mode, propagating through the cavity, generates the high-intensity second-harmonic mode [10–14].

In the present paper we combine both properties of photonic crystals, i.e. localization and the enhancement of nonlinear effects. We study the localized modes of a nonlinear one-dimensional (1D) photonic crystal. In a 1D photonic crystal there are complete bandgaps for light propagating in the direction of periodicity. In this case any defect will produce localized modes within the gaps of the 1D photonic crystal. The radius of localization and the frequency of the localized mode depend on the strength of the defect. Below we assume that the defect is a phase slip [15, 16], i.e. an interruption of periodicity. If the light at fundamental frequency is localized, then due to the nonlinear properties of the crystal it will generate the second-harmonic mode. If the second-harmonic mode is within the bandgap of the photonic crystal then it will be also localized. Below we study the intensity of the generated second-harmonic mode and analyze the conditions under which we have the largest conversion efficiency. The analysis has only been done for a weakly modulated photonic crystal.

2. System of equations

We consider a 1D photonic crystal or periodic modulation of the dielectric constant of the background material in one direction only. We assume that this direction is the x direction and the light is propagating along the same x direction. In this case both the light at the fundamental frequency and the light at the double frequency are polarized in the yz plane. Such a system can be considered as a multi-layer system with the interface of the layers parallel to the yz plane. The propagation of light in the x direction is described by nonlinear wave equations, which in Gaussian units take the following form [17]:

$$\frac{d^2}{dx^2}E_1(x) + \epsilon'(x)\frac{\omega^2}{c^2}E_1(x) = -\chi(x)\frac{8\pi\omega^2}{c^2}E_1^* E_2, \quad (1)$$

$$\frac{d^2}{dx^2}E_2(x) + 4\epsilon''(x)\frac{\omega^2}{c^2}E_2(x) = -\chi(x)\frac{16\pi\omega^2}{c^2}E_1^2, \quad (2)$$

where $E_1(x)$ is an electric field at fundamental frequency ω, $E_2(x)$ is an electric field at the second-harmonic frequency, $\epsilon'(x) = \epsilon(\omega, x)$ and $\epsilon''(x) = \epsilon(2\omega, x)$ are dielectric constants at the fundamental and the second-harmonic frequencies, respectively, and χ is a nonlinear optical coefficient. In the above equations we introduce small periodic modulations of both the dielectric constant and the nonlinear coefficient. Namely, we present them in the form

$$\epsilon(\omega, x) = \epsilon_0(\omega) + \sum_n [\delta\epsilon_n(\omega)e^{2ink_0x} + \text{h.c.}], \quad (3)$$

$$\chi(x) = \chi_0 + \sum_n [\delta\chi_n e^{2ink_0x} + \text{h.c.}]. \quad (4)$$

We assume below that we have a weak periodic modulation of the dielectric medium, i.e. $\delta\epsilon_n \ll \epsilon_0$. In the absence of a defect the periodic modulation will open 1D gaps $\sim nck_0\delta\epsilon_n/(2\epsilon_0)$ at wavelength nk_0, where n is an integer. Since below we are interested only in the in-gap localized modes at the fundamental and second-harmonic frequencies, we keep in equation (3) only those terms with $n = 1$ for the fundamental mode and $n = 2$ for the second-harmonic mode. Then the dielectric constants at the fundamental and second-harmonic frequencies can be presented as

$$\epsilon'(x) = \epsilon_0' + \delta\epsilon_1 e^{2ik_0x} + \text{h.c.}, \quad (5)$$

$$\epsilon''(x) = \epsilon_0'' + \delta\epsilon_2 e^{4ik_0x} + \text{h.c.} \quad (6)$$

Only the periodic terms shown in equations (5) and (6) are responsible for the gap formation around the fundamental and second-harmonic frequencies. The other terms, which are present in the general expression (3) for the dielectric constant, provide only small corrections to the gaps around these frequencies. As a next step we introduce a defect in the form of a phase slip at $x = 0$. This means that the photonic crystal is shifted by $+d$ at $x > 0$ and by $-d$ at $x < 0$, where $d < a/2$. In terms of modulations of the dielectric constants we have the phase shift at $x = 0$

$$\epsilon'(x) = \epsilon_0' + \delta\epsilon_1 e^{2ik_0x}e^{\pm i\phi} + \text{h.c.}, \quad (7)$$

$$\epsilon''(x) = \epsilon_0'' + \delta\epsilon_2 e^{4ik_0x}e^{\pm 2i\phi} + \text{h.c.}, \quad (8)$$

where '+' and '−' signs correspond to $x > 0$ and $x < 0$, respectively, and $\phi = 2k_0d = 2\pi d/\lambda$.

The presence of the phase slip introduces localized modes within the gaps of the photonic crystal. Below we assume that the light at fundamental frequency is localized within the first bandgap of the photonic crystal. Due to the nonlinear properties of the media of the photonic crystal we expect that the fundamental localized mode will generate second-harmonic localized light. The equations describing the coupling between the fundamental and second-harmonic localized modes can be found from the system of equations (1) and (2). Then for the envelopes of the localized modes we obtain the following equations [18]

$$-ik_0\frac{dA_1}{dx} - V_1e^{\pm i\phi}B_1 = \Delta_1 A_1 - \alpha_1 A_1^* A_2, \quad (9)$$

$$ik_0\frac{dB_1}{dx} - V_1e^{\mp i\phi}A_1 = \Delta_1 B_1 - \alpha_1 B_1^* B_2, \quad (10)$$

$$-i2k_0\frac{dA_2}{dx} - V_2e^{\pm 2i\phi}B_2 = \Delta_2 A_2 - \alpha_2 A_1^2, \quad (11)$$

$$i2k_0\frac{dB_2}{dx} - V_2e^{\mp 2i\phi}A_2 = \Delta_2 B_2 - \alpha_2 B_1^2, \quad (12)$$

where the upper and the lower signs correspond to $x > 0$ and $x < 0$, respectively. Here the envelope functions are defined as

$$E_1(x) = A_1(x)e^{ik_0x} + B_1(x)e^{-ik_0x} \quad (13)$$

$$E_2(x) = A_2(x)e^{i2k_0x} + B_2(x)e^{-i2k_0x}, \quad (14)$$

and we introduce the following notation:

$$V_1 = \delta\epsilon_1(\omega/c)^2, \qquad V_2 = 4\delta\epsilon_2(\omega/c)^2, \quad (15)$$

$$\Delta_1 = k_0^2 - \epsilon_0'(\omega/c)^2, \qquad \Delta_2 = 4k_0^2 - 4\epsilon_0''(\omega/c)^2, \quad (16)$$

$$\alpha_1 = 8\pi\chi_0(\omega/c)^2, \qquad \alpha_2 = 16\pi\chi_0(\omega/c)^2. \quad (17)$$

In the system of equations (9)–(12) we also assumed that the nonlinearity is included only through the zero-harmonic term, χ_0, i.e. we disregard periodic modulations of the nonlinear coefficient. Equations (9)–(12) were derived under the condition that the frequency width of the envelope function is much larger than the corresponding wavelength. For the fundamental mode the width of the envelope function can be estimated as k_0/V_1. Then the derivation of equations (9)–(12) is valid if $k_0^2 \gg V_1$ or $\delta\epsilon_1 \ll \epsilon_0$. This is the condition of weak periodic modulation of the medium.

The meaning of different parameters in equations (9)–(12) is illustrated in figure 1. The positions of the center of the first and the second bandgaps are determined by the conditions $k_0^2 = \epsilon_0'(\omega/c)^2$ (the first bandgap) and $4k_0^2 = \epsilon_0''(\omega/c)^2$ (the second bandgap). In terms of the variables $\epsilon(\omega/c)^2$ the widths of the first and second bandgaps are $2V_1$ and $2V_2$, respectively. The position of the localized fundamental mode is characterized by the distance, Δ_1, from the center of the first bandgap. The localization of this mode is due to the presence of the phase slip. Therefore Δ_1 depends on the parameters of the defect. The frequency of the fundamental mode, i.e. Δ_1, determines the position of the second-harmonic mode, which is characterized by the distance Δ_2 from the center of the second bandgap. If the generated second-harmonic mode is outside the second bandgap, i.e. $|\Delta_2| > V_2$, then the second-harmonic mode can freely propagate through the media and the mode is not localized. If the generated second-harmonic mode is within the second bandgap, i.e. $|\Delta_2| < V_2$, then the second-harmonic mode is localized, i.e. it cannot propagate through the photonic crystal. The relation between Δ_2 and V_2 is determined by the parameters of the medium. Below we consider only the most interesting case, when both the fundamental mode and the second harmonic mode are localized, i.e. $|\Delta_2| < V_2$.

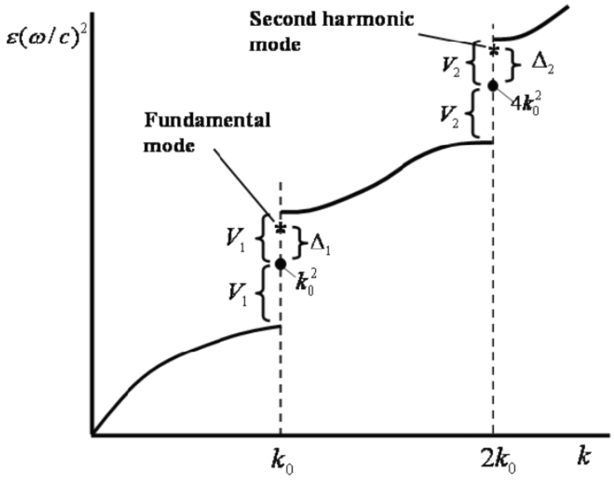

Figure 1. Schematic illustration of the band structure of a one-dimensional photonic crystal with weak modulation of the dielectric constant shown in the plane $\epsilon(\omega/c)^2$–k. The values of V_1 and V_2 determine the width of the first and the second bandgaps. The fundamental mode, localized in the first bandgap due to the presence of the phase slip, is shown by a star. The position of the generated second-harmonic mode is characterized by the distance Δ_2 from the center of the second bandgap, $\epsilon(\omega/c)^2 = 4k_0^2$. If $\Delta_2 < V_2$ then the second-harmonic mode is localized in the second bandgap, otherwise it is delocalized.

3. Generation of the second-harmonic mode

Without nonlinear terms in equations (9) and (10) the localized fundamental mode has the form

$$A_1 = B_1 = (2\gamma_1 I_1)^{1/2}\exp(-\gamma_1|x|), \tag{18}$$

where I_1 determines the total intensity of the light in the localized mode. Here the decrement, γ_1, and the 'frequency', Δ_1, of the localized mode depend on the phase shift, ϕ, as follows:

$$\gamma_1 = (V_1/k_0)\sin\phi, \qquad \Delta_1 = -V_1\cos\phi. \tag{19}$$

We study the generation of the second-harmonic mode by the fundamental localized mode (18). We disregard the effects of the second-harmonic mode on the fundamental mode, i.e. we disregard the terms $\alpha_1 A_1^* A_2$ and $\alpha_1 B_1^* B_2$ in equations (9) and (10), respectively (non-depleted wave approximation). Then to find the generated second-harmonic mode we need to solve the system of equations (11) and (12) with A_1 and B_1 given by equation (18). The solution has the following form:

$$A_2(x) = \frac{\alpha_2\gamma_1 I_1 \mathrm{e}^{\mathrm{i}\delta\phi}}{k_0(\gamma_2+2\gamma_1)}\left[\frac{V_2\cos(\phi+\psi)}{k_0(2\gamma_1-\gamma_2)}(\mathrm{e}^{-2\gamma_1|x|}-\mathrm{e}^{-\gamma_2|x|}) - \frac{\mathrm{e}^{-\gamma_2|x|}}{\sin(\delta\phi)} - \mathrm{i}\mathrm{e}^{-\mathrm{i}\delta\phi}\mathrm{e}^{-2\gamma_1|x|}\right] = B_2^*(x), \tag{20}$$

where we introduce the following notation

$$\delta\phi = \phi - \psi \tag{21}$$

and

$$\psi = \tfrac{1}{2}\cos^{-1}(-\Delta_2/V_2), \qquad \gamma_2 = \frac{V_2}{2k_0}\sin(2\psi), \tag{22}$$

which means that

$$V\mathrm{e}^{\mathrm{i}2\psi} = -\Delta_2 + 2\mathrm{i}k_0\gamma_2. \tag{23}$$

Then the final solution for the second-harmonic mode, E_2, can be written as

$$E_2(x) = \frac{\alpha_2\gamma_1 I_1}{k_0(\gamma_2+2\gamma_1)}\left[\frac{V_2\cos(\phi+\psi)}{k_0(2\gamma_1-\gamma_2)}(\mathrm{e}^{-2\gamma_1|x|}-\mathrm{e}^{-\gamma_2|x|}) - \frac{\mathrm{e}^{-\gamma_2|x|}}{\sin(\delta\phi)}\right]\cos(k_0x+\delta\phi) - \frac{\alpha_2\gamma_1 I_1}{k_0(\gamma_2+2\gamma_1)}\mathrm{e}^{-2\gamma_1|x|}\sin(k_0x). \tag{24}$$

The generated second-harmonic mode is localized if the second-harmonic 'frequency', Δ_2, is within the second bandgap of the photonic crystal, $|\Delta_2| < V_2$, i.e. the second-harmonic mode cannot propagate through the crystal. We should distinguish between the generated localized mode and the real localized mode within the second bandgap. The real localized mode exists without the presence of the fundamental mode and has a form similar to equation (18):

$$A_2^{(l)} = B_2^{(l)} = (2\gamma_2^{(l)})^{1/2}\exp(-\gamma_2^{(l)}|x|). \tag{25}$$

The 'frequency' of this localized mode is

$$\Delta_2^{(l)} = -V_2\cos(2\phi). \tag{26}$$

Below we call the mode (25) the localized mode and the mode (20) the generated localized mode. In general, the frequency of the generated second-harmonic mode, Δ_2, is not equal to the frequency of the localized mode, $\Delta_2^{(l)}$. The condition that the second-harmonic mode is in resonance with the localized mode, i.e. $\Delta_2^{(l)} = \Delta_2$, can be written as $\phi = \psi$. As we can see from equation (24), in this case the intensity of the second-harmonic mode goes to infinity. The reason why we get infinity in the case of the resonance is that in the derivation of equation (24) we disregarded the terms proportional to γ_2/k_0. If we take these terms correctly then we have the cut off at $\delta\phi \approx \gamma_2/k_0$. Finally, for small $\delta\phi$ we obtain

$$E_2(x) = -\frac{\alpha_2\gamma_1 I_1}{k_0(\gamma_2+2\gamma_1)}\frac{\mathrm{e}^{-\gamma_2|x|}}{\sqrt{\delta\phi^2+(\gamma_2/k_0)^2}}\cos(k_0x).$$

Then the total intensity of the generated second-harmonic mode is given by the following expression:

$$I_2 = \int_{-\infty}^{\infty} E_2^2(x)\,\mathrm{d}x = \frac{(\alpha_2\gamma_1 I_1)^2}{2k_0\gamma_2(\gamma_2+2\gamma_1)^2}\frac{1}{\delta\phi^2+(\gamma_2/k_0)^2}.$$

The maximum value of the intensity, I_2, is realized at $\delta\phi = 0$ and equals

$$I_2 = \left(\frac{\alpha_2\gamma_1 I_1}{\gamma_2[\gamma_2+2\gamma_1]}\right)^2\left(\frac{k_0}{2\gamma_2}\right). \tag{27}$$

We can see that the width of the intensity maximum is a function of the non-resonant parameter, $\delta\phi$, is narrow $\sim\gamma_2/k_0 \ll 1$. At the same time the value of I_2 at the maximum is enhanced by a factor $(k_0/\gamma_2)^2 \gg 1$ compared to its value outside of the resonance, i.e. at $\delta\phi \sim 1$.

From equation (27) we can see another tendency in the generation of the second-harmonic mode. Namely, to have the largest intensity of the generated second-harmonic light we need to have the smallest γ_2. This means that the size of the generated localized mode should be as large as possible. At the same time the size of the fundamental mode should be small, i.e. γ_1 should be large. This means that the second-harmonic mode is generated within the origin of the defect, so we need to have the largest intensity of the fundamental mode there. Then the second-harmonic mode will occupy the whole space within its localization length. The upper limit for the localization length of the generated second-harmonic mode is determined by disorder and other types of the defects present in the photonic crystal. Here, we also want to mention that the most efficient generation of the second-harmonic mode does not mean that the spatial sizes of the localized fundamental and the generated second-harmonic modes should be the same.

We can also analyze the spatial distribution, $I_2(x) = |E_2(x)|^2$, of the intensity of the generated second-harmonic mode. The maximum value of the intensity can be another characteristic of the generated mode. We can see from equation (24) that if $\gamma_2 \neq 2\gamma_1$ then the intensity has a maximum at $x = 0$ and at small $\delta\phi$ we have

$$I_{2,\max} = I_2(x=0) = \frac{\alpha_2^2 \gamma_1^2 I_1^2}{k_0^2(\gamma_2 + 2\gamma_1^2)^2} \left(\frac{\cos(\delta\phi)}{\sin(\delta\phi)} \right)^2. \quad (28)$$

A different situation occurs when $\gamma_2 = 2\gamma_1$. In this case from equation (24) we obtain

$$E_2(x) = -\left[\frac{\alpha_2 I_1}{4k_0}\right] e^{-\gamma_2|x|} \left\{ \left[|x| \frac{V_2 \cos(\phi+\psi)}{k_0} + \frac{1}{\sin(\delta\phi)} \right] \cos(k_0 x + \delta\phi) + \sin(k_0 x) \right\}, \quad (29)$$

i.e. $E_2(x)$ has a term with the linear dependence on x. Assuming that $\delta\phi$ is small we can find expression for the intensity of the generated second-harmonic mode:

$$I_2(x) = \left[\frac{\alpha_2 I_1}{4k_0}\right]^2 e^{-2\gamma_2|x|} \times \left\{ |x| \frac{V_2 \cos(\phi+\psi)}{k_0 \sin(\delta\phi)} + \frac{1}{\sin^2(\delta\phi)} \right\}. \quad (30)$$

The intensity has a maximum at $x = x_0$,

$$x_0 = \frac{1}{2\gamma_2} - \frac{k_0}{2V_2 \cos(\phi+\psi)\sin(\delta\phi)}. \quad (31)$$

The value of the intensity at this point is

$$I_{2,\max} = \frac{\alpha_2^2 I_1^2}{16k_0^2} \left[\frac{V_2 \cos(\phi+\psi)}{k_0 \gamma_2 \sin(\delta\phi)} \right] e^{-2\gamma_2 x_0}. \quad (32)$$

The maximum at point x_0 exists only if $x_0 > 0$, which means that $\delta\phi$ should not be very small, i.e. $V_2 \sin(\delta\phi) > \gamma_2 k_0$. If $\delta\phi$ is small, i.e. $\delta\phi < \gamma_2 k_0 / V_2$, than the intensity maximum is at $x = 0$ and is given by equation (28). Comparing equations (28) and (32), we can say that if $\gamma_2 = 2\gamma_1$ then the dependence of the intensity maxima of the second-harmonic mode on $\delta\phi$ has the following form:

$$I_{2,\max} \propto \begin{cases} 1/\delta\phi & \text{if } \delta\phi > \gamma_2 k_0 / V_2 \\ 1/(\delta\phi)^2 & \text{if } \delta\phi < \gamma_2 k_0 / V_2. \end{cases} \quad (33)$$

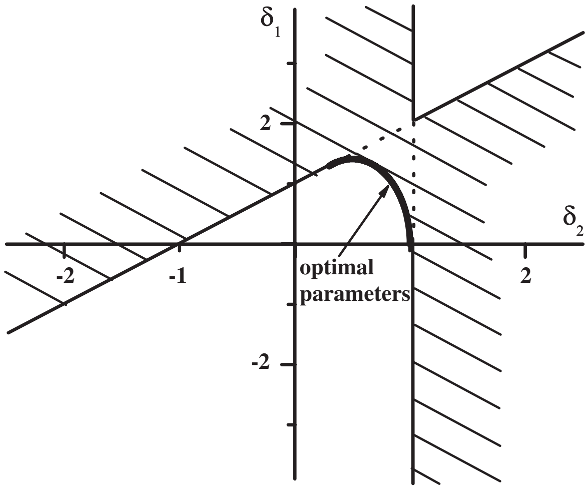

Figure 2. The dashed region illustrates a domain of parameters of the photonic crystal for which the resonant phase slip can be realized. The corresponding phase shift is given by equation (36). The boundaries of the domain are determined by the lines $\delta_2 = 1$, $\delta_1 = 1 + \delta_2$ and $\delta_1 = [8\delta_2(1-\delta_2)]^{1/2}$. The thick solid line, $\delta_1 = [8\delta_2(1-\delta_2)]^{1/2}$, shows the optimal parameters of the photonic crystal.

4. Realization of the resonance condition

The resonance condition, i.e. the condition that the frequency of the generated second-harmonic mode is equal to the frequency of the localized mode within the second bandgap, can be written as $\psi = \phi$. Then, at resonance, we can find from equations (15), (16), and (19) the following relation:

$$\delta\epsilon_2 \cos(2\phi_r) - \epsilon'' = \delta\epsilon_1 \cos(\phi_r) - \epsilon', \quad (34)$$

where ϕ_r is the angle corresponding to the resonance condition, i.e. $\psi = \phi = \phi_r$. If we introduce 'dimensionless' dielectric constants

$$\delta_1 = \delta\epsilon_1/(\epsilon_0' - \epsilon_0''), \qquad \delta_2 = \delta\epsilon_2/(\epsilon_0' - \epsilon_0''), \quad (35)$$

then the solution of equation (34) can be written as

$$\cos(\phi_r) = \frac{\delta_1 \pm \sqrt{\delta_1^2 - 8\delta_2 + 8\delta^2}}{4\delta_2}. \quad (36)$$

Equation (36) also determines the parameters of photonic crystal, δ_1 and δ_2, for which the phase slip with the resonance condition exists, i.e. $0 < \phi_r < \pi/2$. The region of valid parameters δ_1 and δ_2 is shown in figure 2 and is bounded by the lines $\delta_2 = 1$, $\delta_1 = 1 + \delta_2$ and $\delta_1 = [8\delta_2(1-\delta_2)]^{1/2}$. Therefore, for any point in the dashed region in figure 2 we can choose the phase slip with phase shift $\phi = \phi_r$, given by equation (36), so that the generated second-harmonic mode has the same frequency as the localized mode in the second bandgap.

Within the dashed region in figure 2 we can also find the optimal parameters of the photonic crystal so that the system becomes less sensitive to any inaccuracy in the design of the phase slip. Namely, we define the optimal parameters of photonic crystal in the following way.

For any point in the dashed region in figure 2 there is a value of the angle ϕ_r. If we assume that there is an error in construction of the phase slip, so that $\phi = \phi_r + \delta_\phi$, then this error produces the shift between the angles ψ and ϕ and violates the resonance condition. To find the shift between ψ and ϕ we express the angle ψ from equations (15), (16) and (19) in terms of parameters of the photonic crystal. The expression has the following form:

$$\delta_2 \cos(2\psi) = \delta_1 \cos(\phi) - 1. \tag{37}$$

Then the difference between the angles ψ and ϕ is

$$\psi - \phi = (\phi - \phi_r)\left[1 - \frac{\delta_1}{4\delta_2 \cos(\phi_r)}\right]. \tag{38}$$

The smallest value of $|\psi - \phi|$ corresponds to $\cos(\phi_r) = \delta_1/2\delta_2$. Then taking into account equation (36) we obtain that the optimal parameters of the photonic crystal are describe by

$$\delta_1 = [8\delta_2(1-\delta_2)]^{1/2}. \tag{39}$$

This equation is shown by thick solid line in figure 2. Along this line the angle ϕ_r is changed from 0 to $\pi/2$.

5. Conclusion

The largest convergence efficiency of the localized fundamental mode is realized only under the resonance condition. The resonance condition means that the frequency of the second-harmonic mode is equal to the frequency of the localized mode in the second bandgap. The resonance condition can be achieved only if the parameters of the photonic crystal are in the region shown in figure 2. For each set of parameters from this region the phase shift, which corresponds to the resonance condition, can be found from equation (36). There are also optimal parameters of the photonic crystal for which the generation of the second-harmonic mode becomes less sensitive to variation of the phase shift, ϕ, i.e. to violation of the resonance condition. In practice, the parameters of photonic crystals can be modified by tailoring the unit cell structure of photonic crystals.

The generation of the second-harmonic mode in the structure, studied in the present paper, has already been discussed in [19]. In [19] an expression for the intensity of the second-harmonic mode, generated due to propagation of the fundamental mode through a 1D periodic photonic structure with a linear defect, has been derived on the basis of a Green function method. The main outcome of [19] is that generation of the second-harmonic mode is enhanced if the fundamental mode is in the resonance with the localized mode of the defect. What we study in the present paper is a nonlinear localized mode of a defect in 1D photonic crystal. We show that to have the most efficient generation of the second-harmonic mode within the localized region we need to have a double resonance property. This means that both the fundamental mode and the second-harmonic mode should be eigenmodes of the defect. We also derive the condition that the parameters of photonic crystal should satisfy to realize the double resonance defect.

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