Light tunneling inhibition in array of couplers with longitudinal refractive index modulation

Yaroslav V. Kartashov[1,*] and Victor A. Vysloukh[2]

[1]*ICFO-Institut de Ciencies Fotoniques and Universitat Politecnica de Catalunya, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain*

[2]*Departamento de Fisica y Matematicas, Universidad de las Americas–Puebla, Santa Catarina Martir, 72820 Puebla, Mexico*

**Corresponding author: Yaroslav.Kartashov@icfo.es*

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We consider light tunneling inhibition in a periodic array of optical couplers due to the specially designed longitudinal and transverse modulation of the refractive index. We show that local out-of-phase longitudinal modulation of refractive index in channels of directional couplers in combination with the global refractive index modulation between adjacent couplers allow simultaneous suppression of both local and global energy tunneling inside each coupler and between adjacent couplers. This enables the localization of light in single waveguide despite the remarkable difference of corresponding local and global energy tunneling rates.

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Waveguide arrays offer exceptional opportunities for the control of light propagation [1,2]. Additional degrees of freedom appear if the refractive index varies also in the direction of light propagation. Such structures are capable to support discrete diffraction-managed solitons [3–5] and allow a flexible control of beam propagation direction [6,7]. Dynamic localization of light in photonic structures with longitudinal modulation of guiding parameters undoubtedly is among the most interesting optical phenomena. Such a localization was predicted and observed in waveguide arrays [8–13] and optical couplers [14–17]. Different tools for the control of light tunneling were developed, such as periodic bending [8–10,14,15] or out-of-phase modulation of refractive index of adjacent guides [11–13,17]. All previous efforts were focused on photonic structures with a single characteristic energy exchange scale between neighboring guides. However, the periodic array of optical couplers serves as an illuminating example of a photonic structure where a rapid local energy exchange between guides in each coupler coexists with a slow global energy tunneling into adjacent couplers. The presence of two characteristic energy tunneling scales in this system makes the problem of light localization in a single channel especially challenging, since one may expect that simple longitudinal modulation usually adopted in waveguide arrays will not yield inhibition of tunneling. Note that the potential analogy between optical and quantum problems [18] broadens the interest to this optical setting, which is similar to one-dimensional dimer model of quantum mechanics [19].

In this Letter we report on light tunneling inhibition in a periodic array of optical couplers due to especially designed longitudinal and transverse modulations of the refractive index. We show that by properly selecting the law of longitudinal modulation a relatively slow energy exchange between adjacent couplers in the array and a rapid energy exchange between channels of individual couplers can be inhibited simultaneously that results in the diffractionless propagation of single-channel excitations at certain resonant values of the modulation frequency.

The propagation of laser radiation along the ξ axis of periodic array of couplers is described by the Schrödinger equation for the normalized complex field amplitude q,

$$i\frac{\partial q}{\partial \xi} = -\frac{1}{2}\frac{\partial^2 q}{\partial \eta^2} - pR(\eta,\xi)q, \qquad (1)$$

where η and ξ are the normalized transverse and longitudinal coordinates, respectively, while the parameter p describes the refractive index modulation depth. The global refractive index distribution is described by the function $R=\Sigma_{k=-\infty}^{+\infty}R_k$, where the refractive index profile of the kth coupler is given by $R_k=[1+\mu_s\sin(\Omega_s\xi)\pm\mu_l\sin(\Omega_l\xi)]G(\eta+w_s/2+kw_l)+[1-\mu_s\sin(\Omega_s\xi)\pm\mu_l\sin(\Omega_l\xi)]G(\eta-w_s/2+kw_l)$, where $G(\eta)=\exp(-\eta^6/w_\eta^6)$, w_s is the separation between channels inside each coupler, w_η is the channel width, w_l stands for the distance between centers of couplers, while the signs $\pm$ correspond to even/odd values of $|k|$. This profile corresponds to the local out-of-phase harmonic modulation of the refractive index inside two channels of each coupler with a spatial frequency Ω_s and a modulation depth μ_s, and simultaneous global out-of-phase modulation of the refractive index between neighboring couplers with spatial frequency Ω_l and modulation depth μ_l [see Fig. 1(a) for a representative example of such an array of couplers]. Further we set $w_\eta=0.3$, $w_s=1.6$, $w_l=4.0$, and $p=7$. Notice that the longitudinal refractive index modulation not only changes propagation constants of guided modes, but it also modifies coupling between waveguides due to the modification of guided mode profiles and overlap integrals that affect the rate of diffraction in the structure.

Figure 1(b) shows a usual diffraction spreading for the case of excitation of a single channel in the central coupler in the absence of longitudinal modula-

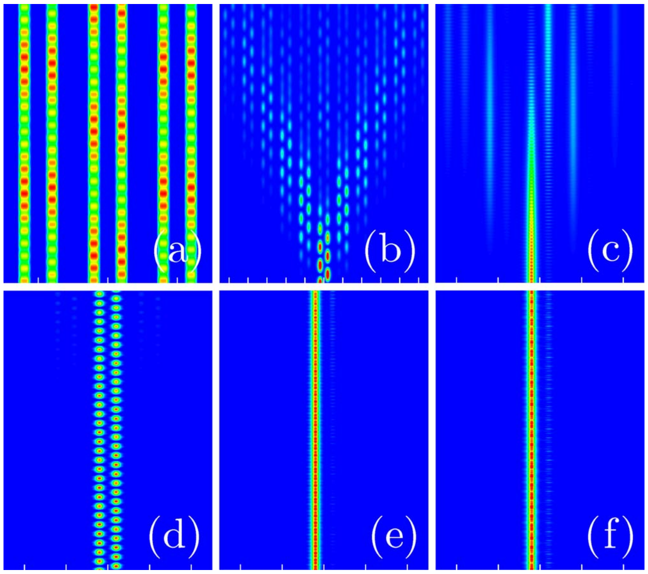

Fig. 1. (Color online) (a) Example of ξ-modulated array of couplers. (b) Discrete diffraction in unmodulated array. Propagation dynamics in modulated array at (c) $\mu_s=0.2$, $\mu_l=0$, $\Omega_s=2.77\Omega_b$; (d) at $\mu_s=0$, $\mu_l=0.2$, $\Omega_l=2.84\Omega_b$; (e) at $\mu_s=0.2$, $\mu_l=0.1$, $\Omega_s=2.77\Omega_b$, $\Omega_l=1.23\Omega_b$; and (f) at $\mu_s=\mu_l=0.15$, $\Omega_s=2.09\Omega_b$, $\Omega_l=0.91\Omega_b$. The propagation distance in (b) is $L=15T_b$, while in (c)–(f) it is $L=30T_b$. White ticks at the bottom of each image indicate centers of couplers.

tion. We use linear guided mode of a single isolated guide as an initial condition for the numerical integration of Eq. (1) (other input beam shapes yield qualitatively similar results). One can observe fast local oscillations inside individual couplers (spatial frequency of intensity beatings is given by $\Omega_b=2\pi/T_b$, where for our parameters $T_b=21.6$) and slow global light spreading across the array due to light tunneling between adjacent couplers. Figure 1(c) illustrates an attempt of light tunneling inhibition using out-of-phase refractive index modulation only inside individual couplers ($\mu_s\neq 0$, $\mu_l=0$). Notice that the modulation frequency Ω_s and the depth μ_s selected correspond to the optimal light tunneling inhibition in an isolated coupler. While such a modulation drastically suppresses energy exchange inside couplers (note that the suppression is remarkable, but it cannot be complete) it cannot suppress light tunneling to neighboring couplers. Analogously, if only modulation between couplers is present ($\mu_s=0$, $\mu_l\neq 0$), one can effectively suppress energy exchange between the couplers but not beatings inside the input coupler [Fig. 1(d)]. This indicates that simple single-frequency longitudinal refractive index modulation does not allow one to achieve tunneling inhibition in system with two characteristic energy tunneling scales, and one has to resort to a more complicated simultaneous local and global longitudinal modulation of the refractive index with $\mu_s,\mu_l\neq 0$. The key issue is thus the optimal selection of parameters of such a modulation.

As a criterion of optimization we used the distance-averaged energy flow $U_{1\,\mathrm{m}}$ trapped in the input channel of the central coupler as well as the distance-averaged energy flow $U_{2\,\mathrm{m}}$ in the central coupler,

$$U_{1\,\mathrm{m}}=L^{-1}\int_0^L \mathrm{d}\xi\int_{-w_s}^0 |q(\eta,\xi)|^2\mathrm{d}\eta/\int_{-w_s}^0 |q(\eta,0)|^2\mathrm{d}\eta,$$

$$U_{2\,\mathrm{m}}=L^{-1}\int_0^L \mathrm{d}\xi\int_{-w_l/2}^{w_l/2} |q(\eta,\xi)|^2\mathrm{d}\eta/\int_{-w_l/2}^{w_l/2} |q(\eta,0)|^2\mathrm{d}\eta.$$

A characteristic feature of light tunneling inhibition is the resonant behavior of the distance-averaged energy flow trapped in the input channel of the central coupler $U_{1\,\mathrm{m}}(\Omega_s)$ as well as the distance-averaged energy in the entire central coupler $U_{2\,\mathrm{m}}(\Omega_l)$ as shown in Fig. 2. Figure 2(a) depicts $U_{1\,\mathrm{m}}$ dependence on the frequency Ω_s for nonzero μ_s in the absence of global modulation, while Fig. 2(b) illustrates $U_{2\,\mathrm{m}}$ dependence on Ω_l for nonzero μ_l in the absence of local modulation. Notice that the resonant peaks in the $U_{1\,\mathrm{m}}(\Omega_s)$ dependence are remarkably sharper. Interestingly, the frequencies of primary resonances (i.e., resonances that occur for largest Ω_s or Ω_l values) do not differ considerably for $U_{1\,\mathrm{m}}(\Omega_s)$ and $U_{2\,\mathrm{m}}(\Omega_l)$ dependencies from Fig. 2. Figure 2(c) exemplifies almost linear dependencies of the principal resonance frequency Ω_{r1} and the frequency of the second resonance Ω_{r2} on the depth of global modulation μ_l at $\mu_s=0$. It should be stressed that the resonances in Figs. 2(a) and 2(b) correspond to the suppression of coupling either inside couplers or between couplers, but the overall localization that can be characterized by the combined localization criterion $U_{\mathrm{tm}}=U_{1\,\mathrm{m}}U_{2\,\mathrm{m}}$ remains low (i.e., U_{tm} is considerably smaller than 1) in both cases because only one type of modulation is present.

Figure 3 demonstrates the combined localization criterion as a function of modulation frequencies Ω_s

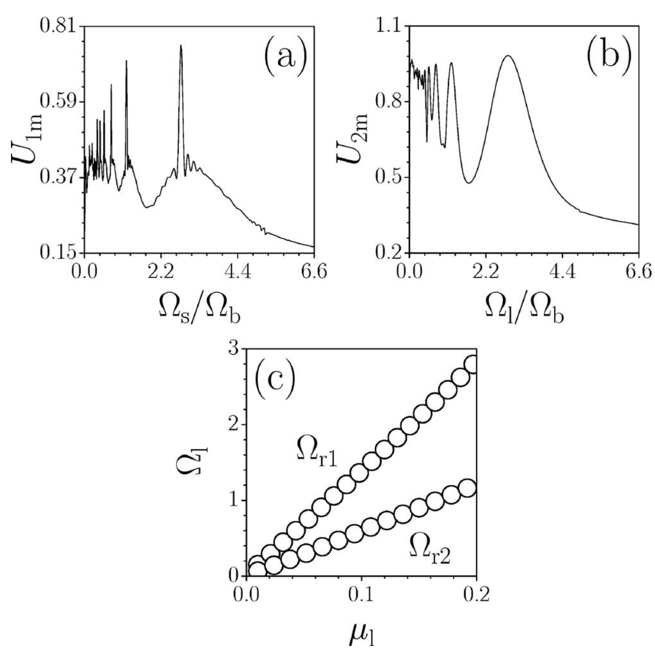

Fig. 2. (a) Distance-averaged energy flow in the input channel versus Ω_s at $\mu_s=0.2$, $\mu_l=0$. (b) Distance-averaged energy flow in the input coupler versus Ω_l at $\mu_s=0$, $\mu_l=0.2$. (c) Frequencies of first and second resonances versus μ_l for $\mu_s=0$.

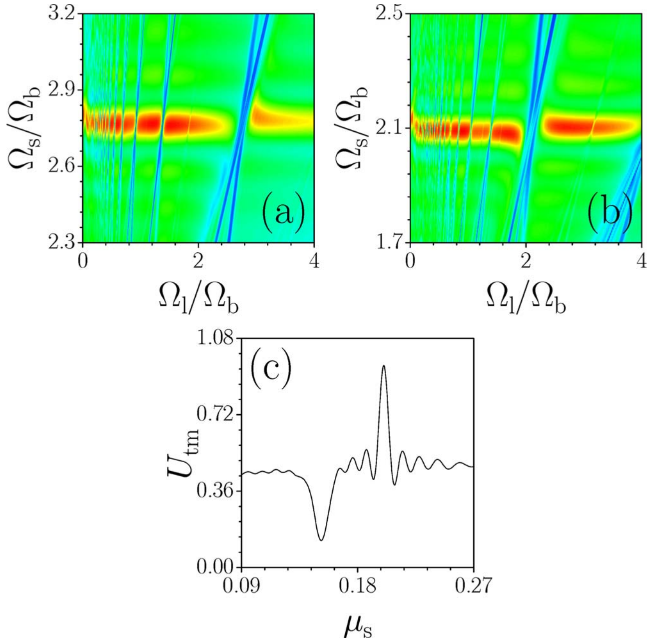

Fig. 3. (Color online) The product of distance-averaged energy flows $U_{\mathrm{tm}}=U_{1\,\mathrm{m}}U_{2\,\mathrm{m}}$ versus modulation frequencies Ω_s and Ω_l at (a) $\mu_s=0.20$, $\mu_l=0.10$ and (b) $\mu_s=0.15$, $\mu_l=0.15$. Red regions correspond to strongest inhibition of tunneling when $U_{\mathrm{m}}\approx 1$, while in blue regions one has strongest delocalization when $U_{\mathrm{m}}\to 0$. (c) U_{tm} versus μ_s at $\mu_l=0.1$, $\Omega_s=2.77\Omega_b$, $\Omega_l=1.23\Omega_b$.

and Ω_l for the simultaneous local and global longitudinal modulation of the refractive index for the cases when $\mu_s\neq\mu_l$ [Fig. 3(a)] and when $\mu_s=\mu_l$ [Fig. 3(b)]. The combined localization criterion U_{tm} attains a maximal value when the energy tunneling between channels of individual coupler and between neighboring couplers is suppressed simultaneously. Importantly, the strongest overall localization with $U_{\mathrm{tm}}\approx 1$ (or the principal resonance for the combined modulation) always appears in the vicinity of the Ω_s value that corresponds to light tunneling inhibition inside individual couplers, and even small detuning of Ω_s from this resonant value leads to remarkable diminishing of localization. The $U_{\mathrm{tm}}(\Omega_l)$ dependence is characterized by the narrow bands of strong delocalization around the frequencies $\Omega_l=\Omega_s/n$, where $n\geq 1$ is an integer, while the maxima of U_{tm} corresponding to the overall inhibition of tunneling appear exactly in between these delocalization bands. For a fixed Ω_s the comparable inhibition of tunneling can be achieved for several Ω_l values. Figure 3(c) illustrates the dependence of the combined localization criterion on the local modulation depth μ_s when μ_l, Ω_s, and Ω_l are fixed and correspond to the strongest global resonance. Typical features of $U_{\mathrm{tm}}(\mu_s)$ profile are the sharp localization peak and the well-defined localization minimum, which appear due to almost linear dependence of resonant frequencies on the modulation depth μ_s [see also Figs. 2(a)–2(c)]. The examples of complete light tunneling inhibition are shown in Figs. 1(e) and 1(f) for the case of combined longitudinal modulation with $\mu_s,\mu_l\neq 0$. One can see that by properly selecting corresponding modulation frequencies Ω_s and Ω_l one can simultaneously suppress energy exchange between channels of the coupler and between neighboring couplers so that upon propagation the light remains in the excited channel.

Summarizing, we showed that out-of-phase longitudinal modulation of the refractive index in the channels of directional coupler in combination with the modulation of the refractive index between adjacent couplers allow a precise control of tunneling despite a remarkable difference of corresponding energy exchange scales. This may be useful for the creation of multichannel optical couplers where output patterns can be altered dramatically by only slight modifications in the longitudinal refractive index modulation frequency and where even weak nonlinearities may substantially affect switching dynamics.

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