Nonlinearity-induced broadening of resonances in dynamically modulated couplers

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Received March 30, 2009; accepted July 21, 2009;
posted August 13, 2009 (Doc. ID 109410); published September 4, 2009

We report the observation of nonlinearity-induced broadening of resonances in dynamically modulated directional couplers. When the refractive index of the guiding channels in the coupler is harmonically modulated along the propagation direction and is out-of-phase in two channels, coupling can be completely inhibited at resonant modulation frequencies. We observe that nonlinearity broadens such resonances and that localization can be achieved even in detuned systems at power levels well below those required in unmodulated couplers. © 2009 Optical Society of America

OCIS codes: 190.0190, 190.6135.

The precise control of light evolution is of major importance in optics [1,2]. When the refractive index in both transverse and longitudinal directions is varied, a number of tools for tuning the propagation dynamics become available. Such structures can be used to manage diffraction in waveguide arrays [3,4], where diffraction-managed solitons can form [5,6]; it can be also used to drag solitons in the transverse plane [7,8] or to initiate soliton center oscillations and shape conversions [9,10]. Dynamic localization (DL) in waveguide arrays and coherent destruction of tunneling (CDT) in directional couplers are possible when the waveguides are modulated periodically in the propagation direction, either by curvature [11–16] or widths or refractive index oscillations [17,18]. DL and CDT are resonant effects, occurring only for a specific modulation amplitude and frequency. Recently, it was suggested that nonlinearity may cause a broadening of such resonance [19], when the so-called nonlinear coherent destruction of tunneling (NCDT) yields a tunneling inhibition also in structures with a frequency slightly detuned from the resonance and for powers well below the formation of solitons in unmodulated systems. In this Letter we experimentally study NCDT in a directional coupler where the refractive index is modulated along the propagation direction and out-of-phase in the two channels. We observe that nonlinearity yields a broadening of resonances proportional to the input power in a certain parameter range. We address here only the two-channel coupler, but similar results may be encountered in more-complicated systems, such as waveguide arrays.

Our model is based on the nonlinear Schrödinger equation for the dimensionless field amplitude q, governing the propagation of cw light along the ξ axis of a two-channel coupler,

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

Here, η and ξ are the normalized transverse and longitudinal coordinates, while p describes the refractive index amplitude. The waveguides in the coupler are described by $R(\eta,\xi)=[1+\mu\sin(\Omega\xi)]\exp[-(\eta+w_s/2)^6/w_\eta^6]+[1-\mu\sin(\Omega\xi)]\exp[-(\eta-w_s/2)^6/w_\eta^6]$, using super-Gaussian profiles for each channel fitted to the shape of the real waveguides in our sample [20]. The longitudinal modulation amplitude is μ, whereas Ω is the longitudinal modulation frequency. The waveguide width and spacing are characterized by w_η and w_s. We set $w_\eta=0.3$ (equivalent to 3 μm) and $w_s=3.2$ (equivalent to 32 μm). We also set $p=2.78$, corresponding to a refractive index of $\sim 3.1\times 10^{-4}$. In all simulations we used the input $q|_{\xi=0}=Aw(\eta)$, with $w(\eta)$ as the shape of the fundamental linear mode of a single waveguide and A as the input amplitude.

In the unmodulated linear device ($\mu=0$) light periodically couples between both channels if only one of them is excited. We define the beating period T_b as the distance at which light returns to the input waveguide after one complete cycle (accordingly, the beating frequency is $\Omega_b=2\pi/T_b$). For our set of parameters we find $T_b=100$. A longitudinal out-of-phase modulation of the refractive index in the channels yields inhibition of coupling for particular values of Ω [15–17]. To characterize localization, we use the distance-averaged power fraction trapped in the excited channel $U_m=L^{-1}\int_0^L d\xi \int_{-\infty}^0 |q(\eta,\xi)|^2 d\eta / \int_{-\infty}^0 |q(\eta,0)|^2 d\eta$, where L is the sample length. This criterion shows very similar features as the output power distribution but is smoother and more suited for a theoretical analysis. The function $U_m(\Omega)$ is characterized by multiple resonances. Here, we consider only the principal resonance at the largest frequency Ω_r (Fig. 1), which grows with increasing longitudinal modulation depth μ [Fig. 1(a)]. For moderate μ we find $\Omega_r \sim \mu$. In the limit $\mu \to 0$ one finds $\Omega_r \to \Omega_b/2$. The half width of the principal resonance $\delta\Omega/\Omega_b$ defined at $U_m = 0.7$ is a monotonically decreasing function of the distance L [Fig. 1(b)]. To understand the impact of nonlinearity on the resonance, we perform an averaging over a sufficiently long distance L. However, the value $\delta\Omega/\Omega_b$ at $L \to \infty$ is determined mostly by the amplitude A of the input beam, since in this limit a vanishing resonance width occurs only for a vanishing amplitude A. In contrast, in our calculations the resonance width is always finite owing to the nonzero power used in the initial conditions. In Fig. 1(c) we show how a variation of μ shifts the principal resonance. In the vicinity of the resonance we find $U_m(\Omega) \approx \mathrm{sinc}[\alpha L(\Omega - \Omega_r)] + K$, which is a direct consequence of averaging an oscillating function over a large distance.

In Fig. 2(a) it is illustrated that the resonance broadens with increasing A. The resonance width grows almost linearly with input power $\sim A^2$, corresponding to [20]. The resonance broadening is shown in Fig. 2(c), where curves 1 and 2 correspond to small and moderate A, respectively. The broadening of the resonance can be considerable even at moderate amplitudes, which are well below the critical amplitude $A_{\mathrm{cr}} \sim 0.42$ required for coupling suppression in the unmodulated system.

The light dynamics is visualized in Fig. 3. The light evolution in an unmodulated coupler is shown in Fig. 3(a). Figures 3(b)–3(d) depict a modulated coupler slightly detuned from the resonance for different input amplitudes. The localization increases with increasing input amplitude owing to the broadening of the resonance.

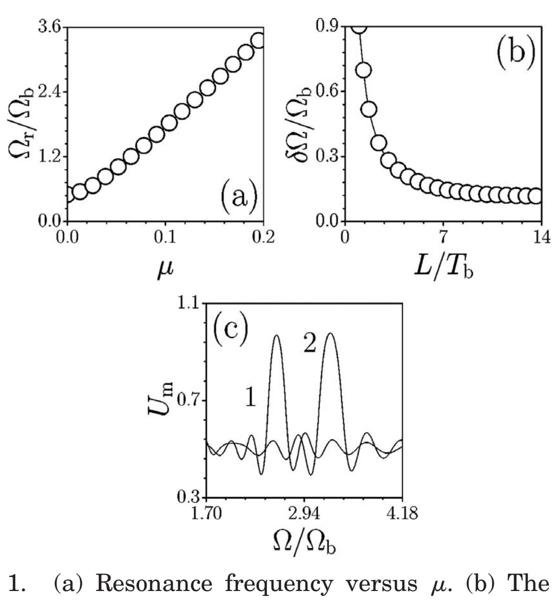

Fig. 1. (a) Resonance frequency versus μ. (b) The half width of resonance curve defined at the level $U_m = 0.7$ versus the coupler length at $\mu = 0.19$ and $A = 0.1$. (c) U_m versus Ω/Ω_b at $A = 0.1$, $L = 8T_b$ for modulation depth $\mu = 0.15$ (curve 1) and $\mu = 0.19$ (curve 2).

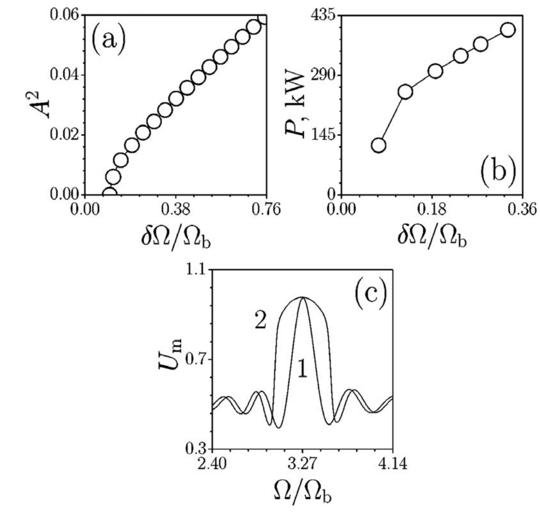

Fig. 2. (a) Theoretically calculated A^2 value versus the half width of resonance curve defined at the level $U_m = 0.7$ at $\mu = 0.19$ and $L = 8T_b$. (b) Experimentally obtained dependence of input peak power required for 70% localization in the launching channel versus normalized detuning from resonance frequency. (c) U_m versus Ω/Ω_b at $\mu = 0.19$, $L = 8T_b$ for input amplitudes $A = 0.03$ (curve 1) and $A = 0.15$ (curve 2).

To confirm these trends experimentally we fabricated a sequence of samples in high-quality fused silica using the femtosecond laser-writing technique [4]. For the experimental analysis of our predictions, we launched light at $\lambda = 800$ nm in one waveguide using a 2.5× objective (NA=0.05). The end facet of the sample was imaged on a CCD camera, using a 10× objective (NA=0.25). The induced index change δn depends on the writing speed v approximately as $\delta n \approx \alpha \exp(-v/\beta) + \gamma$, where the constants α, β, and γ are fitted numerically to the experimental results [20]. A sinusoidal index change along the individual guides is then achieved by varying the writing speed as $v = \beta \ln(\alpha/[p + \mu \sin(\Omega z) - \gamma])$. The sample length was 105 mm, and waveguide spacing was 32 μm. The beating period is $\sim$115 mm, corresponding to $T_b = 100$. The guides exhibit an average refractive index of $\sim 3.1 \times 10^{-4}$ and a modulation amplitude of $\approx 2 \times 10^{-5}$. For these parameters, the principal resonance is found at $\Omega_r \approx 0.180$ mm^{-1} (i.e., $\Omega_r \approx 3.27\Omega_b$). To analyze localization in the vicinity of Ω_r, we fabri-

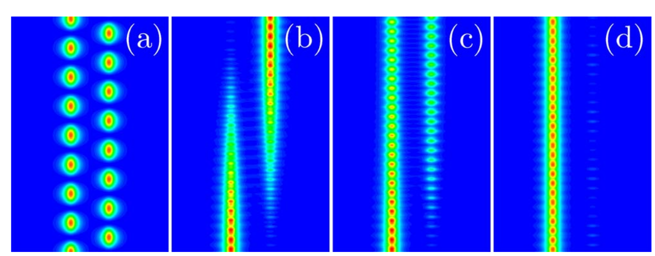

Fig. 3. (Color online) Propagation dynamics in (a) unmodulated coupler at $\mu = 0.00$, $A = 0.01$, and modulated couplers at (b) $\mu = 0.19$, $A = 0.01$, (c) $\mu = 0.19$, $A = 0.12$, (d) $\mu = 0.19$, $A = 0.24$. Propagation distance is $L = 8T_b$, while modulation frequency in (b)–(d) is $\Omega = 3.10\Omega_b$. In all cases left waveguide is excited at $\xi = 0$.

Table 1. Localization Power as a Function of the Modulation Frequency

Ω [mm^{-1}]	P [kW]
0.180	50
0.176	140
0.173	250
0.170	300
0.167	340
0.165	370
0.162	400

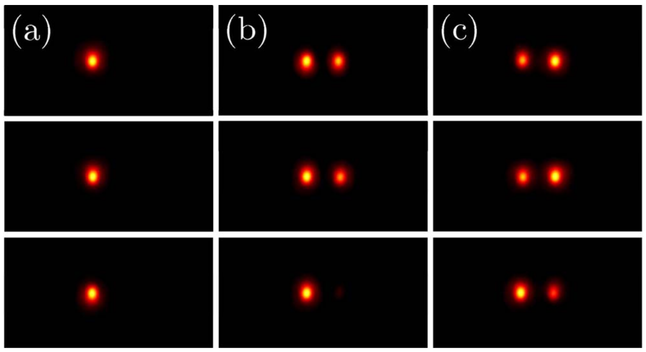

Fig. 4. (Color online) Output intensity distributions for an excitation of the left channel of the modulated coupler when (a) $\Omega = 3.27\Omega_b$, (b) $\Omega = 3.15\Omega_b$, and (c) $\Omega = 3.04\Omega_b$. The input peak power is 50 kW in the first row, 250 kW in the second row, 340 kW in the third row.

cated couplers with frequencies $\Omega = 0.180$, 0.176, 0.173, 0.170, 0.167, 0.165, and 0.162 mm^{-1}.

The width of the resonance curve $\delta\Omega/\Omega_b$ was defined using those powers, where 70% of input power still remains in the excited channel. In the resonant coupler, a minimal power of 50 kW was injected to achieve localization. The powers for the detuned samples defined by the criterion mentioned above are shown in Fig. 2(b) and Table 1. The circles represent measured points, including the error of about 15 kW. For very small detuning the dependency is nonlinear, as confirmed by the continuous model [see Fig. 2(a)]. However, $P(\delta\Omega)$ increases linearly as detuning increases, which is consistent with results of [20] obtained for a discrete model. Representative output patterns for different modulation frequencies are shown in Fig. 4. Note that in all cases the left waveguide was excited. In the left column, [Fig. 4(a)] the coupler at the resonance frequency is shown. For all applied input powers, the light remains localized. In contrast, in detuned coupler with $\Omega = 0.173$ mm^{-1} [Fig. 4(b)] the light at 50 kW couples strongly into second guide (first row). At 250 kW input power, about 70% of the injected light remains in the excited channel (second row), defining the width of the resonance curve. For higher peak powers (e.g., 340 kW in the third row), light almost completely localizes in the excited waveguide. When frequency is detuned from resonance even further, i.e., when $\Omega = 0.167$ mm^{-1}, at 50 kW a large fraction of the light couples into the second waveguide [see first row of Fig. 4(c)]. Even at 250 kW the localization is just slightly larger (second row). More than 70% of the light remains in the excited guide only above an input power of 340 kW (third row), which again defines the width of the resonance curve.

In conclusion, we observed nonlinearity induced resonance-broadening in longitudinally modulated couplers. Localization was observed in couplers with a modulation frequency considerably detuned from resonance at powers well below the threshold required in unmodulated system. We confirmed that the dependence of power on resonance width is approximately linear.

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