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Ultrasharp edge filtering in nanotethered photonic wires

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Optical filtering is a key function in all-optical networks. Simultaneously to a large rejection—at least 20 dB—the sharpest band edge is desired for a very selective spectral response. Such a sharp-edge reflector can also be of interest in optical modulation or switches. Ring-resonator-based filters have been extensively investigated: custom-designed filter shape can be obtained implementing a large number of coupled ring resonators. A very sharp edge filter has also been theoretically proposed in a photonic crystal environment, including phase-shift elements aside the PhC membrane thickness. The 2×2 transmission matrix product of a system essentially reads \( M_R M_\phi M_M \phi^N \), where \( N \) is the number of periods and the four matrices account for reflection (\( M_R \)), cavity coupling (\( M_M \)), and the two identical phase sections \( M_\phi \) parametrized by the half-period phase \( \phi = \pi \lambda / \ell (s + t) \). The result for \( N = 100 \) and \( \gamma = 0.0014 \) (notation of Ref. 4), plotted in Fig. 2(b) as a transmission map versus \( \ell / \text{normalized frequency} \) and normalized period \( \ell / (s + t) / \text{normalized frequency} \), is seen to be a staggered alternation of “enhanced DBR” and “inhibited DBR” stop-bands located across the deep resonator notch frequency. The DBR stop-bands would be of nearly constant depth without the resonator. Here, we

In our case, the photonic wire is suspended in air through regularly spaced nanotethers [Fig. 1(a)]. The intercations can be considered as a reflector on the wire, while the tethers themselves can be considered as lossy resonators with partial reflection at their two ends due to the dielectric mismatch. When wires are relatively wide (\( w = 0.8 \text{ to } 0.6 \mu \text{m} \)), the nanotethers have been shown to operate mainly as a DBR, at a high order due to the large spacing/wavelength ratio (spacing \( s = 1 \text{ to } 10 \mu \text{m} \)). When considering a narrower wire [\( w = 0.3 \text{ to } 0.4 \mu \text{m} \), Fig. 1(b)], the side-coupling to the tethers becomes larger. We elucidate the positive role of the reactive (resonant) contribution of the tethers based on an extrapolation of Ref. 4, where the interplay of side-resonance and reflection to attain sharper edges was clarified.

We first consider the basic periodic extrapolation of Ref. 4 [Fig. 2(a)], with cavities centered between weak DBR individual elements, here simply modeled by a reflectivity \( r = 0.05 \). The 2×2 transmission matrix product of a system essentially reads \( (M_R M_\phi M_M \phi^N) \), where \( N \) is the number of periods and the four matrices account for reflection (\( M_R \)), cavity coupling (\( M_M \)), and the two identical phase sections \( M_\phi \) parametrized by the half-period phase \( \phi = \pi \lambda / \ell (s + t) \). The result for \( N = 100 \) and \( \gamma = 0.0014 \) (notation of Ref. 4), plotted in Fig. 2(b) as a transmission map versus \( \ell / \text{normalized frequency} \) and normalized period \( \ell / (s + t) / \text{normalized frequency} \), is seen to be a staggered alternation of “enhanced DBR” and “inhibited DBR” stop-bands located across the deep resonator notch frequency. The DBR stop-bands would be of nearly constant depth without the resonator. Here, we

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**Ultrasharp edge filtering in nanotethered photonic wires**

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Within a suspended photonic wire, the periodically-spaced nanotethers sustaining the wire can behave as damped transverse resonators that interact with the partially reflecting effect of the wire-tether intersection, and thus modify the Bragg reflection mechanism. This specific resonant mechanism is explored using a transfer matrix model, and is shown to result in an ultrasharp filter edge. This sharp behavior is evidenced experimentally on 300–400-nm-wide InP suspended wires through transmission data and further consolidated by optical low coherence reflectometry time-frequency analysis. © 2010 American Institute of Physics. [doi:10.1063/1.3513279]

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**FIG. 1.** (Color online) (a) Schematic of the tethered wire. (b) Scanning electron microscope picture of a suspended wire (spacing \( s = 2 \mu \text{m} \), tether length \( d = 2 \mu \text{m} \), wire width \( w = 0.3 \mu \text{m} \), tether width \( t = 70 \text{ nm} \), and membrane thickness \( e = 260 \text{ nm} \)).
focus on the DBR stop-band, we do not comment the sharpening of the deep resonator notch, noting that fundamentally both reactive phenomena interact and may potentially produce sharper features for any of them. The alternation obtained is a natural consequence of a standing wave pattern between reflectors, switching from node to antinode field at the center position of the cavities, that is, a switch for a step in the 4φ round-trip phase (hence Δφ = π/2).

We further extrapolate a model more suited to the nanotethered wire case by localizing the side-resonators with the reflectors, see Fig. 2(e), hence by using now a transmission matrix product \( M_{\text{cav}} M_{\text{DBR}} \) with \( r = 0.05 \). We also add large losses in \( M_{\text{cav}} \) since the featureless tethers are expected to be poor stublike resonators. The resonant terms in \( M_{\text{cav}} \) now read \( (γ/\{ω−ω_{\gamma}+iy\}) \) with a large \( γ \) value, \( γ/\omega_{\gamma} =0.08 \), whereas \( γ/\omega_{\gamma} =0.0014 \). We then observe [Figs. 2(d) and 2(e), plot and map] that in addition to the broad dip due to radiation losses centered at \( ω_{\gamma} \), there is a strong asymmetry of DBR stop-band strength between either sides of this dip.

Furthermore, the stop-band nearest to the dip acquires the desirable sharp edge on its short wavelength side. The overall behavior of stop-band strength is dictated by the real-part of the resonant term, \( \text{Re}[γ/\{ω−ω_{\gamma}+iy\}] \), manifesting its “reactive” origin; therefore the tails of this effect scale with the slow decay \( (ω−ω_{\gamma})^{-1} \) instead of the Lorentzian decay \( (ω−ω_{\gamma})^{-2} \) of the central dip around \( ω=ω_{\gamma} \).

Suspended tethered wires were fabricated on a 260 nm thin suspended InP membrane. An established process based on ICP (Inductively Coupled Plasma) etching of nanopatterns followed by a selective etching of the sacrificial layer and a supercritical drying is used, see Fig. 1(b). The following parameters were investigated: wire width \( w=0.3 \) to \( 0.8 \) μm, tether spacing \( s=1 \) or \( 2 \) μm, tether length \( d=1 \) to \( 2 \) μm, and tether width \( t=70 \) or \( 90 \) nm.

Transmission measurements are performed on 680-μm-long photonic wires, on an end-fire fiber set-up including a polarization-maintaining tunable source in TM-like polarization (electric field E is vertical). In Fig. 3, the spectrally resolved transmission is plotted in the case of \( w=0.4 \) μm, \( s=2 \) μm, \( d=2 \) μm, and \( t=70 \) nm. We observe two resonances spaced by 146 nm, which corresponds to the free spectral range at \( Δ=1510 \) nm for a cavity size \( s=2 \) μm, in agreement with the group index \( n_g η_{\gamma} \) calculated in Ref. 7. We clearly observe that the resonance at 1450 nm is shallow, while the one at 1590 nm exhibits a very sharp edge: the transmission drops by 25 dB on a 3 nm span. The 10 dB smoother trough at 1560 nm is attributed to a damped tether resonance, as introduced in the model. The shallow resonance lies far on the left of this trough while the sharp one is the resonantly enhanced one, in agreement with the calculated mechanism.

These resonances have been analyzed by OLCR, a powerful technique implemented to investigate slow light modes in PhC waveguides. The same numerical algorithm exploiting the phase sensitive reflectogram in the spectral domain has been used; a 2 nm bandwidth sweeping filter is applied to produce the time–wavelength reflection maps plotted in Fig. 4. The OLCR source has a spectral range limited to 80 nm, which prevents both resonances of Fig. 3 to be observed simultaneously. In order to compare this coupled resonance to a classical Bragg resonance, we chose a wide wire \( w = 0.8 \) μm where the coupled resonant sharpening effect disappears and we selected the Bragg resonance occurring in the OLCR spectral range. On Fig. 4(b), the classical Bragg effect produces a small and shallow resonance, the rear facet is visible, and a double-round trip is also visible with no increased delay. In the case of the “enhanced Bragg” effect...
[Fig. 4(a)], the time delay is largely increased, which evidences the fact that the strongly enhanced feedback is "assisted" by the side resonators, with a longer energy storage. This is opposite to the trend of a stronger classical Bragg reflector, in which the smaller penetration would translate into a shorter delay.

The longer tether resonators ($d=2 \, \mu m$) exhibit the steepest filtering since they support a higher order mode of larger Q factor. For broader ($t=90 \, nm$) or shorter ($d =1 \, \mu m$) tethers, the coupled resonant mechanism is not observed since these geometries correspond to resonators of lower Q factor. For larger tether spacing ($s>2 \, \mu m$), the structure becomes too fragile and breaks. Higher Q resonators should lead to sharper filters with the same DBR bandwidth.

We have experimentally evidenced within a photonic wire held by regularly spaced thin nanotethers (70 nm) a coupled resonant mechanism leading to very sharp spectral filtering. The resonance takes place in each tether much like in a stub, and all resonators are coupled through the waveguide wire. The measured behavior can be understood by using a transfer matrix simulation that generalizes the approach of Fan.4