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ABSTRACT

Among open resonators of mesoscopic size, we have shown recently that broad waveguides with Littrow diffraction at one of their boundaries could produce a set of sharp resonances in a silicon-on-insulator implementation at 1550 nm. We draw here two perspectives: firstly, we make use of a fundamental theory initially proposed in 1995 by Demkov and Ostrovsky, for Landau-Zener phenomena in the case of crossing manifolds, to explain the flatness of bands in such broad periodic waveguides. Secondly, we capitalize on the fact that longer waveguides behave as multiple series resonators to investigate the $\chi(3)$ nonlinear the triply resonant wavelength conversion process. The free-spectral-range of our waveguides are in the 15 – 30 nm range. Triply resonant conversion demands equal spacing, thus controlled dispersion, which could be achieved by playing with multiple resonators and the rest of the parametric space of these systems.

Keywords: broad waveguides, slow-light, multiple Fabry-Perot, triple resonance, nonlinear response.

1. THE DEMKOV-OSTROVSKY COUPLING THEORY

In dielectric structures, slowing down light amounts to couple waves either to localized energy-storage materials, or to more macroscopic resonators. If periodicity is concerned, localizing energy amounts to get flat bands, and thus, classically, to consider *a single* gap[1]. *Multiple gaps* are however an interesting situation as they can lead to localize energy at multiple frequencies, a desirable goal in the context of, for instance, frequency combs. Two decades ago, Demkov and Ostrovsky have given the formal solution of the very basic problem of crossing of two equidistant manifolds [2, 3], as drawn in Fig. 1(a), when an identical coupling V prevails amid any member of manifold 1 and manifold 2.

The result is a periodic function of V, with a band pattern illustrated in Fig. 1(b). It becomes mathematically flat for the particular value $V = 1/\pi$ in normalized units. The application context was that of Landau-Zener tunnelling among Rydberg states of atoms [4], thus we indicated formally the time, and the eigenstates are nothing but the adiabatic states of the Landau-Zener transition problem (see [5] for photonics analogy). However, for us, this axis is going to be the wavevector, and, as we illustrated elsewhere, the two manifolds are the set of higher-order modes of a broad waveguide [6-11]. The coupling then comes from periodicity, and is only weakly variable vs. mode order, making the Demkov-Ostrovsky model a correct one as a first approximation, and thus allowing for multiple equidistant flatbands in the band picture.

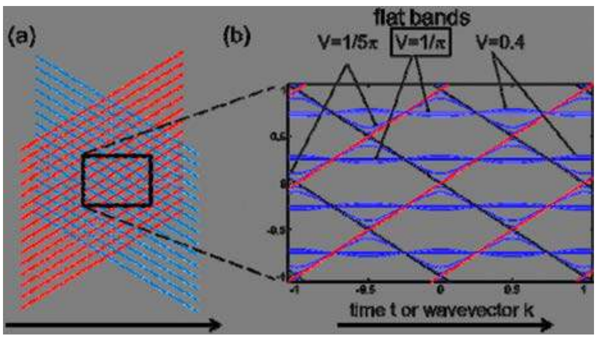

Figure 1: (a) Generic crossing of equally-spaced manifolds controlled by any parameter (wavevector, perturbation,); (b) Demkov-Ostrovsky results a uniform coupling V between the two manifolds states (modes).

2. EXPERIMENT PRINCIPLE

The broad waveguide is made of silicon-on-insulator, processed by the EpixFab facility, hence we use the guide effective index $n_{\text{eff}} \sim 2.8$ as a basic 2D photonic design parameter. Some details are given in Fig. 2. The broad waveguide [Fig. 2(a)] operates with higher-order modes whose underlying plane-wave make a 45° angle with the guide axis. Thus Littrow diffraction forms regular 45° triangle structures, and there is a resonance between each reflection on the grating [6, 9-11]. The order *m* of these resonances is typically $m \sim 50$ or $m \sim 75$ at 1550 nm, depending on the designed width *w*. This order can be seen either as the round-trip path $4\sqrt{2}wn_{\mathrm{eff}}$ or as the interacting guided mode order, the two modes having, in a scalar view, a field $E \sim \sin(m\pi y/2w)\exp(i\pi z/a)$ at the boundary of the first Brillouin zone edge[12].

Each resonance acts as a Fabry-Perot (FP), so that a waveguide of some length behaves exactly as Fabry-Perot in series (see also an electronic analogy[13]): although there is no transmission mirror and the guide looks as a defect-free periodic structure, light goes serially between the different resonating areas. Fig. 2(b) shows a T8 structure that supports the equivalent of three FP resonators. Fig. 2(c) shows the "single-FP" T4 device, and its access guide and out-coupling gratings. The setup is further sketched in Fig. 2(d) [8].

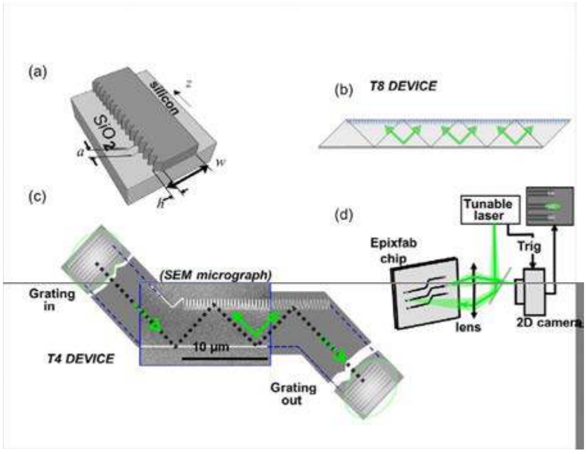

Figure 2: (a) Sketch of a typical EpixFab chip/sample; (b) in-plane layout for triple resonance T8; (c) Device view with grating coupler and access guides. (d) Optical setup with a tuneable laser triggering the camera.

3. EXPERIMENTAL RESULTS

Results are obtained for devices of different length T4, T6 T8, different orders $m = 50$ associated to ~ 30 nm free-spectral-range (FSR) or $m = 75$ associated to 20 nm FSR, and different teeth shape obtained by varying the aspect ratio height/period = h/a. This parameter dictates the coupling strength, and thus plays a role analogous to the general Demkov-Ostrovsky parameter V described above, controlling the degree of flatness [8]. In Fig. 3, we show in normalized frequency units $u = a/\lambda$ the transmission spectra of two T8 devices.

We see for instance that the case $h/a = 4.00$ corresponds to non-flat bands, thus broader minibands and smoother peaks, whereas $h/a = 3.00$ is closer to the critical coupling condition $V = 1/\pi$, and nice and sharp triplets are seen, at least two peaks are prominent in each cluster, three in some others. We have proposed that these FP peaks are more robust than those that would be obtained from standard Bragg mirrors in transmission for instance, because in a lossy mirror, transmission is generally mode degraded than reflection.

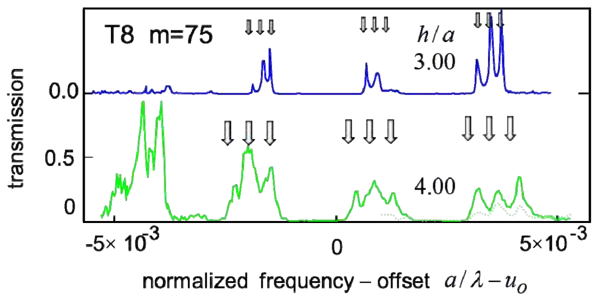

Figure 3. Experimental spectra of T8 samples with variable degree of resonance, depending on the teeth aspect ratio h/a *as indicated. A normalized and offset abscissa has been used to align spectra clusters.*

4. NONLINEAR TRIPLE RESONANCE

Exploiting these systems for nonlinear optics is made attractive by the possibility of triple resonance. In principle, a device akin to a FP with multiple resonance can accomplish triply resonant wavelength conversion $\omega_{idler} = 2\omega_{pump} - \omega_{signal}$. But in a solid state resonator, the material dispersion is a well-known impediment to good phase matching: the FSR tends in general to diminish at higher frequencies (normal dispersion), and very high design constraints have to be included by optogeometric means (exact waveguide shape…) to get equalized FSR.

Here, we propose that dispersion is relaxed, but that the multiple peaks in the long devices can be used to get phase matching even in the presence of substantial dispersion. Ideally, in a structure "T(2N+2)" equivalent to N FP in series, one could choose among any three peaks in a collection of 3N peaks to get as close as possible to equal spectral distances $|\omega_{pump} - \omega_{signal}|$ and $|\omega_{pump} - \omega_{signal}|$.

For instance, a typical dispersion compensation would involve to choose peak1, peak1 and peak 2or 3 respectively in each three-peak cluster of Fig. 3, so as to restore the spectral distance diminished by material dispersion or y flat waveguide dispersion. Another criterion is the overlap of the resonant fields. As each peak is a Bloch mode of the ensemble of N FP cavities, its repartition among the N resonators is specific in amplitude and phase. Thus, nonlinear effects may be coherently destroyed or reinforced, according to these amplitudes and phases, notably when one forms the field products $(E_{pump})^2 E_{signal}$ for various cases and looks at their projection on E_{idler} to see whether the nonlinear $\chi(3)$ source term at idler frequency is on resonance or not (see also [14]).

Our analysis based on known symmetries of Bloch modes has led us to discard single, double and triple FP and focus on $N = 4$. We modelled the field in a four-FP structure thanks to a coupled mode model in the style of H. Haus [15], whereby each FP field evolution is resonant and fed by the adjacent cavities. For instance, a typical transmission spectrum is given in Fig. 4(a). The Q factor of the system is around 5000, well in line with our experimental results ($Q \sim \delta u/u$).

We also used the same approach to introduce scalar source terms acting on the whole field of each FP cavity, and we evaluated separately the "intra-cavity" overlap integral to check that the nonlinear source terms were well fed by the pump and signal fields.

A typical result of such a modelling is the colour map of Fig. 4(b), which shows the strength of the nonlinear response as a function of the pump and idler frequency (causing the signal to be at $\omega_{signal} = 2\omega_{pump} - \omega_{idler}$). The ~ 1.7 % FSR/central frequency ratio is typical of our $m = 75$ structures. The two oblique dashed lines track two matching lines whereby $2\omega_{pump} - \omega_{signal}$ corresponds to a given pair of modes of Fig. 4(a).

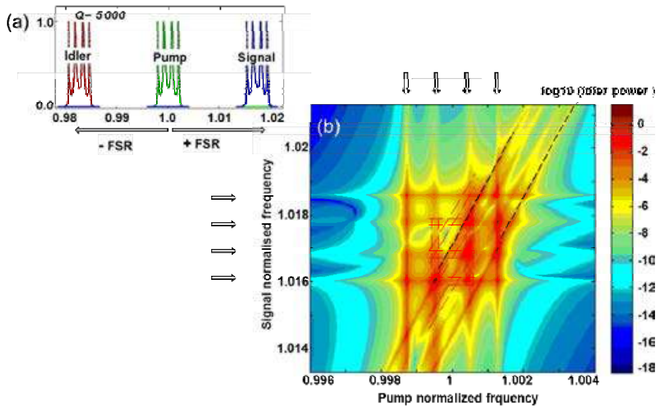

Figure 4: (a) transmission of a four-cavity structure (T10 equivalent); (b) Calculated enhancement map of nonlinear $\chi(3)$ idler generation from a simplified model ; the dashed lines are the phase matching lines for specific modes, the arrows indicate the four frequencies of each resonance number.

The enhancements are seen to be stronger with specific peaks. These are often the more resonant Bloch modes, *i.e.* the extreme ones of the four-peak clusters for one of the two frequencies, but not for both of them. The peak values occurring in this preliminary result, around order of magnitude 1, are not the absolute enhancements related to bulk propagation, prefactors ~ Q^2 have been omitted. More analysis is in progress, but the potential for highly enhanced triply resonant conversion is clearly identified.

In conclusion, we have evidenced the capability of our broad waveguides to serve as resonators with a fundamentally simple structure. Such a structure is *equivalent to multiple Fabry-Perot*, although light never traverses mirrors but only uses reflexion, a feature that we believe to be advantageous. We then use a simplified coupled-mode model to analyse the condition of large $\chi(3)$ enhancement for wavelength-converted signals. Here the magnitude of $\chi(3)$ is found best on the extreme peaks. We also remarked that our system with its 4 peaks at each FSR can help compensate dispersion, which is very interesting for topics such as frequency comb generation[16, 17].

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