Slow-wave wavelength converter

**Dipartimento di elettronica e Informazione*
Politecnico di Milano, via Ponzio 34/5 , 20133 Milano, ITALY.
melloni@elet.polimi.it

Francesco Morichetti, Silvia Pietralunga, Mario Martinelli*
CORECOM, via G. Colombo 81, 20133 Milano, ITALY.
morichetti,pietralunga,martinelli@corecom.it

A novel four-wave-mixing based wavelength converter is presented. The device is based on the slow-wave propagation in a direct-coupled resonator structure, which enhances the conversion efficiency without introducing bandwidth impairments.

Keywords: guided-wave optics, periodic structures, resonators, nonlinear optics.

Introduction

Optical Wavelength Division Multiplexing (WDM) networks require devices able to efficiently shift a modulated signal from an optical carrier to another to prevent wavelength blocking and easing cross connecting. Wavelength converters based on four-wave-mixing (FWM) process offer several advantages [1], such as modulation format transparency and wide spectral response. However, as the efficiency of all-optical interactions in typical nonlinear materials is extremely low, long devices and high pump powers are required to obtain a significant converted power.

It is also well-known that the conversion efficiency may be increased by means of optical resonant structures, such as Fabry-Perot cavities or optical micro-rings, in which nonlinearities are strongly enhanced [2, 3]. However, a high-finesse cavity is required to obtain a strong nonlinear enhancement and hence an efficient wavelength conversion is feasible only on narrow-band optical signals.

On the contrary, when a series of directly coupled resonators are suitably cascaded to realize an optical Slow-Wave Structure (SWS), the enhancement given by the resonant propagation can be exploited without introducing impairments on the spectral response, which can be designed to efficiently fit wide-band channels requirements.

Properties of optical Slow-Wave Structures

An optical SWS consists of a sequence of direct-coupled resonators inserted into or coupled to an optical waveguide. It can be realized, for instance, by cascading partially reflecting elements, such as Bragg gratings, inside an optical waveguide, or by directly coupling a chain of micro-rings (Fig. 1). Even photonic crystals [4, 5] and bulk multilayers could be deployed to build up a SWS. The main property of a SWS is that wave propagation, which is allowed only within a comb of periodic passing bands, is substantially slowed down with respect to propagation in a straight waveguide. To avoid detrimental ripples in the spectral response, the high impedance of the SWS needs to be matched to that of the input-output waveguides by means of few resonators with a suitably lower finesse [6].

If a sufficiently high number of equal resonators are cascaded, an optical wave propagates through the SWS as in a periodic media. By imposing the Bloch condition on the propagating field, the dispersion relationship for a SWS results

$$cos(\beta d) = \frac{sin(kd)}{t}, \qquad (1)$$

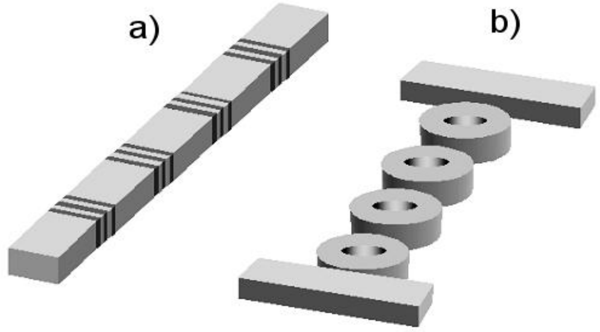

Fig. 1. Two examples of optical direct-coupled resonator SWS: the direct coupled Fabry-Perot SWS (a) and the direct coupled microring SWS (b)

where β is the propagation constant of the SWS, k is the propagation constant of the waveguide and $2d$ is the round trip of each resonator. The field coupling ratio t between two consecutive resonators is assumed wavelength independent for simplicity. From eq.(1) the bandwidth of each SWS pass-band is straightforwardly derived as

$$B = \frac{2FSR}{\pi} sin^{-1}(t), \tag{2}$$

where the Free Spectral Range, $FSR = c/2n_0d$, is the distance between two consecutive resonant frequencies, and n_0 is the waveguide effective index.

The SWS introduces a chromatic dispersion that is typically several orders of magnitude higher than material and waveguide dispersion. To the first order, the SWS-induced dispersion leads to the reduction of the optical group velocity v_g with respect to the wave velocity $v = c/n_0$ in an equivalent straight waveguide. The velocity reduction is expressed by the *slowing ratio* $S = v/v_g$, which may be directly derived from eq.(1),

$$S = \frac{cos(kd)}{\sqrt{t^2 - sin^2(kd)}}. \tag{3}$$

As shown in Fig. 2 the group velocity v_g of an infinitely long SWS assumes its maximum value $v_g(f_0) = c/n_0t$ at each resonance, then v_g drops to zero moving towards the band edges. Note as v_g may be arbitrarily reduced just by reducing the coupling ratio t, even though the bandwidth B narrows as well. At resonance the second order dispersion β_2 vanishes, so an optical pulse can propagate undistorted for several resonators.

As a consequence of the group velocity reduction, the effective length covered by the propagating field inside the SWS is enhanced by a factor proportional to S with respect to the waveguide physical length. In particular an enhancement equal to $(S + 1)/2$ is found for the progressive wave, whereas $(S - 1)/2$ is obtained for the regressive wave. Also the intra-cavity power is increased with respect to the input power P_{in}, as it happens inside a single optical cavity. The ratio between the power of the regressive wave P_- and the progressive wave P_+ is given by $P_-^2/P_+^2 = (S-1)/(S+1)$ and, by imposing the power conservation condition $P_+ - P_- = P_{in}$, the expressions of $P_+ = (S + 1)P_{in}/2$ and $P_- = (S - 1)P_{in}/2$ are straightforwardly obtained.

Thanks to these properties, SWSs can be efficiently deployed in several nonlinear applications, as shown in the following section, where the performance of a slow-wave wavelength converter are evaluated.

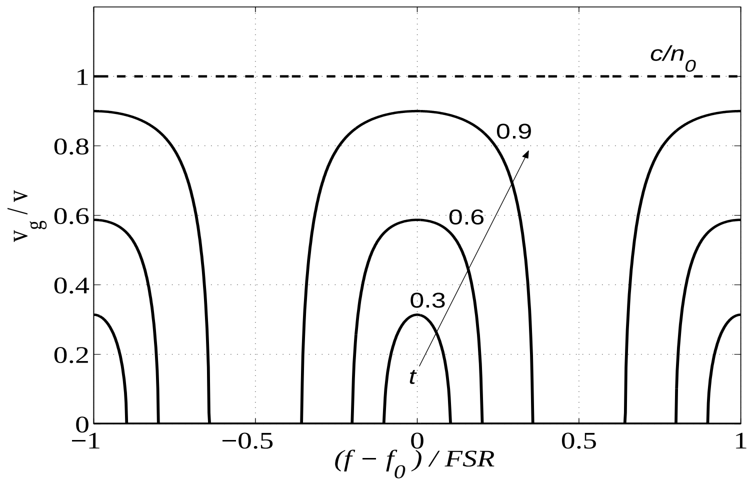

Fig. 2. The group velocity reduction of an infinitely long SWS for three different values of t.

The slow-wave wavelength converter

Let us consider an intense pump and a weak signal tuned at two different SWS resonances, respectively named f_{0p} and f_{0s}. An idler wave is generated by FWM at a third SWS resonance $f_{0c} = 2f_{0p} - f_{0s}$. The slow-wave propagation affects the conversion process by means of the two above discussed effects, that are the intra-cavity power enhancement of all the propagating fields (pump, signal and idler) and the enhancement of the effective interaction length. By introducing these enhancement terms into the expression for FWM wavelength conversion [1], the converted power P_c at the end of a SWS of length L is obtained

$$P_c(L) = \gamma^2 P_p^2 P_s L^2 \left(\frac{S^2+1}{2}\right)^2 \operatorname{sinc}^2\left(\frac{\Delta\beta L}{2}\right), \tag{4}$$

where P_p is the pump power, P_s is the signal power and γ is the well-know nonlinear constant. Eq.(4) shows that the slow-wave propagation increases the FWM based frequency generation by the fourth power of S, so that an extremely high conversion enhancement can be achieved by using SWS made of weakly coupled resonators. Since the SWS bandwidth decreases versus S, an accurate design of the device must be carried out in order to obtain a wide-band high efficiency wavelength converter.

The maximum power that can be converted by a single SWS is limited by the intra-cavity phase mismatch $\Delta\beta = \Delta k\, S$, being $\Delta k = k_s + k_c - 2k_p$ the phase mismatch in the absence of resonators. Since highly nonlinear materials are often highly dispersive, the phase mismatch Δk is mainly due to material dispersion and the second order approximation $\Delta k = \hat{\beta}_2(2\pi\Delta f)^2$ generally holds, where $\hat{\beta}_2$ is the material dispersion coefficient at the pump frequency and Δf is the frequency detuning between f_{0p} and f_{0s}. The converted power reaches its maximum value $P_{c,max}$ after $N_{max} = \pi/dS\Delta k$ cavities,

$$P_{c,max} = P_p^2 P_s \left(\frac{2\gamma}{\Delta k}\right)^2 \left(\frac{S^2+1}{2S}\right)^2, \tag{5}$$

then the power transfer starts to reverse from the converted wave to the pump wave. In eq.(5) the term in the first bracket only depends on the material parameters, whereas the term in the second bracket is related to the SWS.

The converted power can be further increased by cascading several SWS interleaved by suitable linear rephasing devices, so as to realize a *quasi-phase-matched* SWS. Fig. 3 shows the performance of a quasi-phase-matched SWS having B=20GHz, FSR=200GHz and operating a wavelength conversion over 4THz. The SWS provides an enhancement of more than 26dB with respect to an straight waveguide of the same physical length.

In conclusion, we have shown that nonlinear interactions, and specifically frequency mixing phenomena, can be highly enhanced by using waveguiding structures including one or more SWSs. The conversion enhancement is found to be proportional to the fourth power of the slowing ratio, does not implies significant bandwidth impairments and does not depend on the waveguiding material.

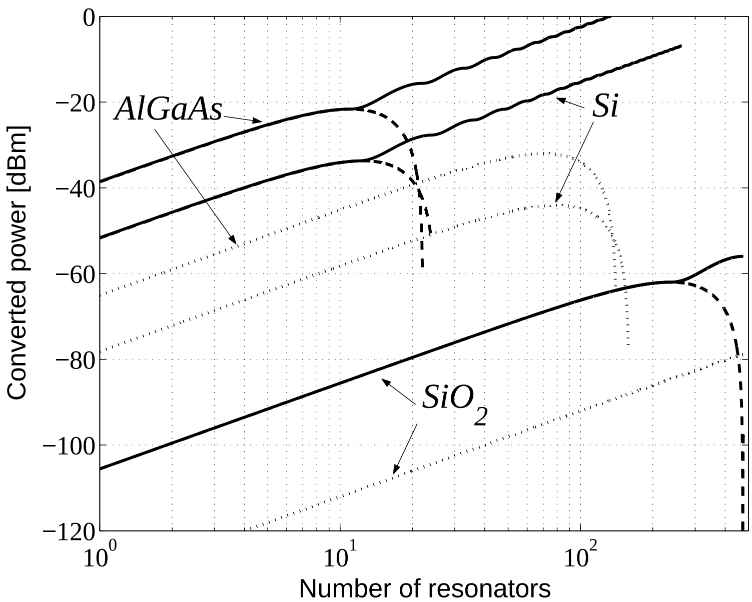

Fig. 3. Solid lines show the performance of a FWM based SWS wavelength converter (B=20 GHz, FSR=200 GHz) for three different nonlinear materials (AlGaAs, Si and SiO2). Dashed lines indicate the inversion of the power transfer from the converted wave to the pump wave in absence of rephasing at the end of the first stage. Rephasing elements are required every 11 resonators for AlGaAs, 12 for Si and 237 resonators for SiO2. Dotted lines represent the converted power in absence of resonators, 26 dB below the SWS converted power. A 100mW pump power and 10mW signal power are used.

References

[1] G. P. Agrawal, *Nonlinear Fiber Optics*, Academic Press, New York, 1999.

[2] P. P. Absil, J. V. Hrynicwicz, B. E. Little, P. S. Cho, R. A. Wilson, L. G. Joneckis, P.-T. Ho, *Opt. Lett.* **25**, 554–556, 2000.

[3] S. Jiang, M. Dagenais, *Appl. Phys. Lett.* **62**, 2757-2759, 1993.

[4] S. Mookherjea, A. Yariv, *IEEE Journal of selected topics in quantum electronics* **8**, 448–456, 2002.

[5] M. Soljacic, S. G. Johnson, S. Fan, M. Ibanescu, E. Ippen, J. D. Joannopoulos, *J. Opt. Soc. Am. B* **19**, 2052-2059, 2002 .

[6] A. Melloni, M. Martinelli, *J. Lightwave Technol* **20**, 296–303, 2002.