Numerical Results for Wavelength Conversion of Superchannels in a Periodically Poled Lithium Niobate Waveguide

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***Abstract*—We report the numerical demonstration of a wavelength conversion for a 200 Gbaud superchannel in a periodically poled Lithium Niobate (`PPLN`)**

I. INTRODUCTION

Recently, coherent optical transmission has started to be deployed in long haul optical networks to enable higher data rates and increase optical reach. Coherent optical carriers could also be combined to create aggregate channels, known as superchannels, in order to achieve spectral efficiency even larger than Nyquist limit and to increase operational flexibility [1]. Optical signal processing may enable fast signal operations in the optical domain without optical-electrical-optical (OEO) conversion. Nonlinear optic wavelength conversion devices based on Quasi-Phase Matching have the advantage that wavelength conversion can be realized for any wavelength in the transparent region of the material. Among these, `PPLN` is a promising solution that allows highly efficient wavelength conversion offering several features such as broad conversion bandwidth, compactness, transparency to data rate and modulation format, and possibility to be incorporated into a polarization insensitive scheme [2].
We numerically demonstrate a wavelength conversion for a 200 Gbit/s super-channel based on the cascaded sum- and difference-frequency generation (cSFG/DFG) in a `PPLN` waveguide. We observed a good consistance between numerical and experimental data. The interaction in the nonlinear optical phenomena is formulated and calculated by the beam propagation method [3].

A. Scenario

The wavelength conversion of a 200 Gb/s super-channel, composed of 4 Nyquist 25 Gbaud QPSK sub-carriers, each at a frequency f_{s_i}, was examined [6]. A first interaction inside the waveguide, between the 4 QPSK sub-carriers and a first pump P_1, opportunely placed at frequency f_{P_1}, generates a copy of each sub-carrier through SFG at frequency $f_{P_1} + f_{S_i}$ (outside C-band). In order to maximize the efficiency of SFG, f_{P_1} must be symmetric to the super-channel with respect to f_{QPM} , which is the quasi phase-matching (QPM) frequency. The condition of symmetry can be achieved either by tuning

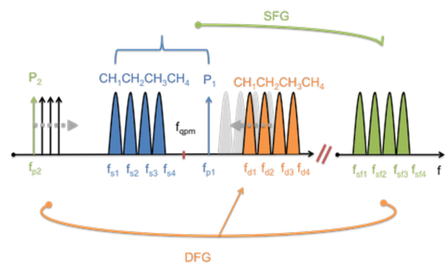

Fig. 1. Frequency conversion in the PPLN.

fP1 or by changing the PPLN temperature. Then, replicas obtained by means of SFG interact with a second pump P_2 at frequency f_{P_2}, through DFG. Thus, DFG generates other replicas in the C-band at frequency $f_{S_i'} = f_{P_1} + f_{S_i} - f_{P_2}$, as shown in Fig. 1.

B. Theoretical Model

The wavelengths must satisfy the following relation,

$$\frac{1}{\lambda_{sf}} = \frac{1}{\lambda_{p1}} + \frac{1}{\lambda_s}, \qquad \frac{1}{\lambda_{df}} = \frac{1}{\lambda_{sf}} - \frac{1}{\lambda_{p2}}. \tag{1a, 1b}$$

Nevertheless, these wavelengths should satisfy the following QPM conditions, called `Tuning Curves`,

$$\frac{2\pi}{\lambda_{sf}} n_{e,sf} - \frac{2\pi}{\lambda_{p1}} n_{e,p_1} - \frac{2\pi}{\lambda_s} n_{e,s} = \frac{2\pi}{\Lambda} \tag{2}$$

$$\frac{2\pi}{\lambda_{sf}} n_{e,df} - \frac{2\pi}{\lambda_{p_2}} n_{e,p_2} - \frac{2\pi}{\lambda_c} n_{e,c} = \frac{2\pi}{\Lambda} \tag{3}$$

where Λ is the period of the periodically domain-inverted structure, and $n_{e,i}$ (i stands for p1, s, sf, p2, df) is the refractive index at the two pumps, SFG, signal, and converted wavelengths, respectively, approximated by the Sellmeier equation. The following derived coupled-mode equations describe propagation and nonlinear interactions among the signals in a `PPLN` waveguide with a length L[4]:

$$\begin{aligned} \frac{dA_{p_1}}{dz} &= -\beta_1^{p_1} \frac{dA_{p_1}}{dt} - \frac{j}{2} \beta_2^{p_1} \frac{d^2 A_{p_1}}{dt^2} + \\ & -j w_{p_1} \kappa_{sf} A_s^* A_{sf} e^{-j \Delta k_p z} - \frac{\alpha}{2} A_{p_1}. \end{aligned} \tag{4}$$

$$\frac{dA_s}{dz} = -\beta_1^s \frac{dA_s}{dt} - \frac{j}{2}\beta_2^s \frac{d^2 A_s}{dt^2} + \\ -jw_s \kappa_{sf} A_{p_1}^* A_{sf} e^{-j\Delta k_p z} - \frac{\alpha}{2} A_s. \quad (5)$$

$$\frac{dA_{sf}}{dz} = -\beta_1^{sf} \frac{dA_{sf}}{dt} - \frac{j}{2}\beta_2^{sf} \frac{d^2 A_{sf}}{dt^2} + \\ -jw_{sf} \kappa_{sf} A_{p_1} A_s e^{-j\Delta k_p z} + \\ -jw_{sf} \kappa_{df} A_s A_{df} e^{-j\Delta k_c z} - \frac{\alpha_{sf}}{2} A_{sf}. \quad (6)$$

$$\frac{dA_{p_2}}{dz} = -\beta_1^{p_2} \frac{dA_{p_2}}{dt} - \frac{j}{2}\beta_2^{p_2} \frac{d^2 A_{p_2}}{dt^2} + \\ -jw_{p_2} \kappa_{sc} A_{df}^* A_{sf} e^{-j\Delta k_c z} - \frac{\alpha}{2} A_{p_2}. \quad (7)$$

$$\frac{dA_{df}}{dz} = -\beta_1^{df} \frac{dA_{df}}{dt} - \frac{j}{2}\beta_2^{df} \frac{d^2 A_{df}}{dt^2} + \\ -jw_{df} \kappa_{sc} A_{p_2}^* A_{sf} e^{-j\Delta k_c z} - \frac{\alpha}{2} A_{df}. \quad (8)$$

where $A_{p1}, A_{p2}, A_s, A_{sf}, A_{df}$ denote the complex electric fields of the two pump, the SF, the signal, and DF waves. β_1^i, β_2^i are the first and second derivatives of the propagation constants with respect to the angular frequency w_i $(i = p1, p2, sf, s, df)$. α, α_{sf}, are the attenuation coefficients of waveguides for the c band wave and SF wave.
The phase mismatching in the SFG (DFG) process are given by

$$\Delta k_p = \frac{2\pi}{\lambda_{sf}} n_{e,sf} - \frac{2\pi}{\lambda_{p_1}} n_{e,p_1} - \frac{2\pi}{\lambda_s} n_{e,s} - \frac{2\pi}{\Lambda} \quad (9)$$

$$\Delta k_c = \frac{2\pi}{\lambda_{sf}} n_{e,sf} - \frac{2\pi}{\lambda_{p_2}} n_{e,p_2} - \frac{2\pi}{\lambda_{p_2}} n_{e,df} - \frac{2\pi}{\Lambda} \quad (10)$$

The SFG (DFG) coupling coefficient in the waveguide are given by

$$\kappa_{sf} = \frac{\frac{\sqrt{2\mu_0}}{c} d_{eff}}{[n_e(\lambda_{sf}) n_{e,p_1} n_{e,s} A_{eff}]^{1/2}} \quad (11)$$

$$\kappa_{df} = \frac{\frac{\sqrt{2\mu_0}}{c} d_{eff}}{[n_{e,sf} n_{e,p_2} n_{e,df} A_{eff}]^{1/2}} \quad (12)$$

where d_{eff} is the effective non linear coefficient and A_{eff} is the effective area interaction. The first and second terms on the right-hand side of the eq. (4), (5), (6), (7), (8), represent the effect of spatial propagation and the third term represents the nonlinear optic effect.
The mentioned equation cannot be solved analytically, then the two effects are calculated separately for each infinitesimal section h in the z direction (Beam Propagation Method). The propagation effect is determined by taking the Fourier transform of the time waveform, and taking the inverse Fourier transform after providing the effect of the propagation of the infinitesimal section for each component. While the nonlinear optic effect was kept into account using the fourth-order `Runge Kutta` method to the differential equation for z, in each infinitesimal section [5].

C. Simulation results

A simulator based on Matlab was built using the characteristic data of our custom PPLN $(L = 30mm, \Lambda = 19.2\mu m)$. We performed the simulation about the mentioned scenario. For the sake of shortness, we have shown in Fig. 2 the

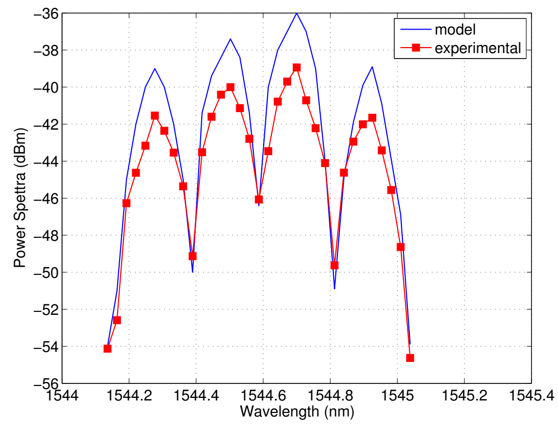

Fig. 2. Experimental and simulation Super channel Spectra

simulation output spectrum of the super channel at the end of the PPLN (in wavelength position determined by the relations 1a, 1b) compared with the experimental spectrum, obtained in an our previous experimental activity [6]. We observed a good consistance between numerical and experimental data even if the spectra do not match completely ($\simeq 2dBm$ for each channel) because of the reflection (multiple cavity reflections) and insertion losses that have been not considered.

II. Conclusion

A wavelength conversion for a 200 Gbit/s superchannel in a `PPLN` was numerically demonstrated and compared with experimental results. Indeed the simulations verified the effectiveness of the PPLN in optical processing and lead us to improve our model for testing other fast network operation, such as switching, dropping and routing.

Acknowledgment

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