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 Gb/s superchannel in a periodically poled Lithium Niobate (PPLN) waveguide.

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 larger than Nyquist limit and to increase operational flexibility [1]. Optical signal processing may enable fast signal operations larger than Nyquist limit and to increase operational flexibility [1].

We numerically demonstrate a wavelength conversion for a 200 Gbit/s super-channel based on the cascaded sum-frequency generation (cSFG/DFG) in a 200 Gbit/s super-channel based on the cascaded sum-frequency generation (cSFG/DFG) in a periodically poled Lithium Niobate (PPLN) waveguide. We observed a good consistence 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 Gb/s 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 $P_1$, opportunistically 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 $f_{P_1}$ 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,

$$\frac{1}{\lambda_{s,f}} = \frac{1}{\lambda_{P_1}} + \frac{1}{\lambda_s}, \quad \frac{1}{\lambda_{df}} = \frac{1}{\lambda_{s,f}} - \frac{1}{\lambda_{P_2}}. \quad (1a, 1b)$$

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

$$\frac{2\pi}{\lambda_{s,f}} n_{e,s,f} - \frac{2\pi}{\lambda_{P_1}} n_{e,p_1} - \frac{2\pi}{\lambda_s} n_{e,s} = \frac{2\pi}{\Lambda}, \quad (2)$$

$$\frac{2\pi}{\lambda_{s,f}} n_{e,df} - \frac{2\pi}{\lambda_{P_2}} n_{e,p_2} - \frac{2\pi}{\lambda_c} n_{e,c} = \frac{2\pi}{\Lambda}, \quad (3)$$

where $\Lambda$ is the period of the periodically domain-inverted structure, and $\lambda_{s,i}$ (i stands for $p_1$, 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]:

$$\frac{d A_{P_1}}{dz} = -\beta_{P_1} \frac{d A_{P_1}}{dt} - \frac{1}{2} \beta_{P_1} \frac{d^2 A_{P_1}}{dt^2} + j w_{P_1} \kappa_{sf} A_{s,f}^* A_{s,f} e^{-j\Delta_k z} - \frac{\alpha}{2} A_{P_1}. \quad (4)$$
\[
\begin{align*}
\frac{dA_s}{dz} &= -\beta_1 A_s - \frac{j}{2} \beta_2 d^2 A_s + j w_s \kappa_s A_{p1} A_s e^{-j \Delta k_{pz}} - \alpha A_s, \quad (5)
\end{align*}
\]
\[
\begin{align*}
\frac{dA_{sf}}{dz} &= -\beta_1 A_{sf} - \frac{j}{2} \beta_2 d^2 A_{sf} + j w_{sf} \kappa_{sf} A_{p1} A_{sf} e^{-j \Delta k_{pz}} + j w_{sf} \kappa_{df} A_s A_{df} e^{-j \Delta k_{cz}} - \alpha A_{sf}, \quad (6)
\end{align*}
\]
\[
\begin{align*}
\frac{dA_{p2}}{dz} &= -\beta_1 A_{p2} - \frac{j}{2} \beta_2 d^2 A_{p2} + j w_{p2} \kappa_{se} A_{df} A_{p2} e^{-j \Delta k_{cz}} - \alpha A_{p2}, \quad (7)
\end{align*}
\]
\[
\begin{align*}
\frac{dA_{df}}{dz} &= -\beta_1 A_{df} - \frac{j}{2} \beta_2 d^2 A_{df} + j w_{df} \kappa_{se} A_{p2} A_{df} e^{-j \Delta k_{cz}} - \alpha A_{df}. \quad (8)
\end{align*}
\]

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. \( \beta_1, \beta_2 \) are the first and second derivatives of the propagation constants with respect to the angular frequency \( \omega_i \) (\( i = p1, p2, s, f, df \)). \( \alpha, \alpha_{sf}, \) 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

\[
\Delta k_p = \frac{2 \pi}{\lambda_{sf}} n_{e,sf} - \frac{2 \pi}{\lambda_{p1}} n_{e,p1} - \frac{2 \pi}{\lambda_s} n_{e,s} - \frac{2 \pi}{\Lambda} \quad (9)
\]

\[
\Delta k_c = \frac{2 \pi}{\lambda_{sf}} n_{e,sf} - \frac{2 \pi}{\lambda_{p2}} n_{e,p2} - \frac{2 \pi}{\lambda_{p2}} n_{e,df} - \frac{2 \pi}{\Lambda} \quad (10)
\]

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

\[
\kappa_{sf} = \left[ \frac{\sqrt{\mu_0 \epsilon}}{\epsilon (\lambda_{sf}) n_{e,p1} n_{e,s} A_{eff}} \right]^{1/2} \quad (11)
\]

\[
\kappa_{df} = \left[ \frac{\sqrt{\mu_0 \epsilon}}{\epsilon (n_{e,sf} n_{p2} n_{e,df} A_{eff})} \right]^{1/2} \quad (12)
\]

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 \( (L = 30 \mu m, \Lambda = 19.2 \mu m) \). We performed the simulation about the mentioned scenario. For the sake of shortness, we have shown in Fig. 2 the 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 consistence between numerical and experimental data even if the spectra do not match completely (\( \simeq 2 \) dBm in 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.

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### REFERENCES