Fiber characterization for single-photon frequency conversion applications

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Abstract. Bragg Scattering Four-Wave mixing (BS-4WM) is used in fibers to frequency shift single photons. We investigate how its phase matching condition can be controlled by changing the fiber temperature. We then are able to optimize the efficiency of the BS-4WM process for selected wavelengths that will ultimately allow a scheme of active multiplexing of single photons.

Optical fibers enable photon transmission over long distances with low losses, and are therefore key parts of quantum communication. To connect different parts of a quantum-optical system, it can also be useful to efficiently convert photons from one frequency to another. BS-4WM recently attracted much interest in various quantum domains, like quantum memories [1], color qubit manipulation [2] and single photons frequency conversion [3]. In this work, we investigate the thermal tunability of BS-4WM in fibers to achieve these frequency shifts that can also be exploited for actively multiplexed single photon sources [4]. As represented in figure 1b, BS-4WM involves two pumps at wavelength λ_{p1} and λ_{p2}. If these two strong pumps are launched into a fiber with a single photon at wavelength λ_i, this photon will be annihilated and a new one will be generated at wavelength λ_s, resulting in an effective shift given by the detuning between the two pumps: ω_i - $\omega_s = \omega_{p1} - \omega_{p2}$. Efficient BS-4WM demands satisfying the phase-matching condition:

$$\delta = [\beta(\omega_i) + \beta(\omega_{p1}) - \beta(\omega_s) - \beta(\omega_{p2}) + \gamma(P_{p2} - P_{p1})]/2 \ll \frac{1}{L} \quad (1)$$

$$\text{With} \quad \beta(\omega) = \frac{S}{8}\left(\frac{-4\pi^2 c^2}{\omega} + \frac{\lambda_0^4 \omega^3}{12\pi^2 c^2}\right) \quad \text{and} \quad \eta = \frac{\kappa^2 \sin(kL)}{k^2} = \frac{P_s(L)}{P_i(0)} \quad (2)$$

$\beta(\omega)$ is the propagation constant of the fiber and is expressed as a function of its zero dispersion wavelength (λ_0) and dispersion slope (S). Because λ_0 has a temperature dependency [5], δ will also be affected by temperature. The conversion efficiency η (for a fiber of length L, with $\kappa = 2\gamma\sqrt{P_1 P_2}$ and $k = \sqrt{|\kappa|^2 + \delta^2}$) is experimentally calculated with the right part of 2. To determine the pumps and single photon input wavelengths giving the most efficient BS-4WM at room temperature, we first characterize the fiber (110 m of sm13 from Fujikura) with the setup depicted in figure 1a. Pumps are two synchronized pulsed lasers, with a duty cycle of 1.10^{-3}, a peak power of 1.9 W., and a repetition rate of 5 MHz: one fixed at 1548.6 nm and the second tunable around 1563 nm. The single photon seed is emulated by a weak CW laser at 1124.5 nm, with a power of 0.6 mW. The results of this characterization are presented in figure 1c (red curve). Temporal walk-off likely explains

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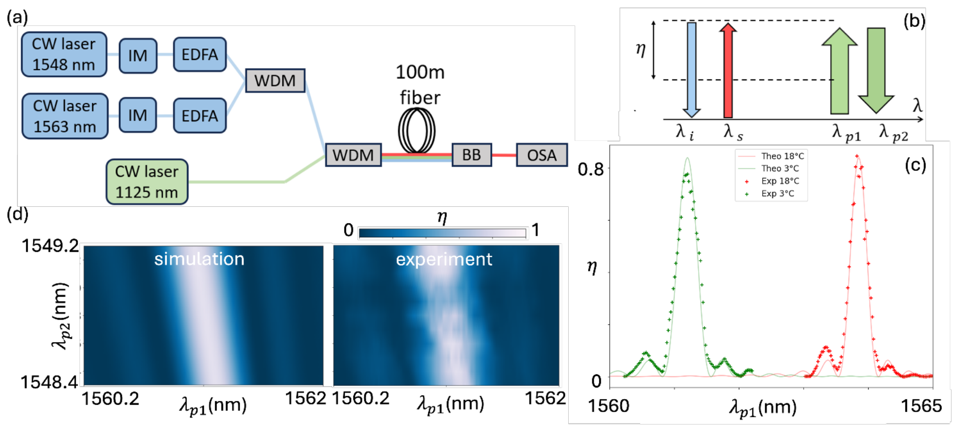

Figure 1. a) Setup used to characterize the fiber. IM : intensity modulation, WDM : wavelength division multiplexer, BB : pump blocking filter, EDFA : optical amplifier; b) BS-4WM scheme, up (down) arrows correspond to photon creation (annihilation); c) Conversion curve for BS-4WM (crosses) compared to a theoretical fit (line). Red line is at 18°C and green one at 3°C. Fixed parameters are λ_{p2} = 1548.6 nm, $P_1 = P_2 = 1.9$W, $L = 100$ m, $\gamma = 2\text{W}^{-1}\text{km}^{-1}$, $S = 100\text{s/m}^3$, $\lambda_0 = 1325.27$ nm for red curve and 1324.85 nm for the green one; d) Map of BS-4WM efficiency for a fiber at 3°C in the theoretical (left) and experimental (right) case.

why the efficiency doesn't reach unity. However, the phase matching bandwidth of 0.5 nm agrees with theoretical prediction. To build our actively multiplexed single photon source photons [4], the BS-4WM must be preceded by spontaneous four waves mixing (SpFWM), ideally in the same fiber. Because both processes have a slightly different phase matching condition, we want to tune one with respect to the other. This can be achieved by controlling the fiber temperature. We realize the same experiment at a decreased temperature of 3°C and extracted the tunability of the BS-4WM. Figure 1c (green curve) shows this 15 K decrease in temperature results in a 2.5 nm shift of the phase matching wavelength λ_i. With formula 2 we calculate the tuning of λ_0 to be 0.028 nm/K.
To conclude, we have shown that it is possible to efficiently shift the wavelength of BS-4WM conversion peak by controlling fiber temperature. We will then investigate the photon noise induced by the pump beam in order to build our single photon source.

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[1] P. J. Bustard and al, *Toward Deterministic Sources: Photon Generation in a Fiber-Cavity Quantum Memory.* Physical Review A **Vol.109, No. 1**p. 013711, 2024.

[2] D. Lee and al, *NOON-state interference in the frequency domain.* Optics express **Vol.33, No. 3**, p. 4595-4603, 2025.

[3] D. Bolotov and al, *Efficient frequency conversion via a wide-spanning intermodal four-wave mixing Bragg scattering process.* Light: Science and Applications **Vol.13, No. 1**, p. 90, 2024.

[4] S. Massar and al, *Resource efficient single photon source based on active frequency multiplexing*. Optics Letters **Vol.46, No. 12**, p. 2832-2835, 2021.

[5] G. Ghosh and al, *Temperature-Dependent Sellmeier Coefficients and Chromatic Dispersions for Some Optical Fiber Glasses*. Journal of lightwave technology **Vol.12, No. 8**, p. 1338-1342, 1994.