Adiabatic Sum-Frequency Conversion

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Abstract: We present a novel technique to achieve both high efficiency and broad bandwidth in SFG process using adiabatic conversion scheme, adapted from NMR and light-matter interaction. The robustness and tunability of the scheme are discussed.

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1. Introduction

Frequency conversion is a key concept in the field of nonlinear optics. In this process, light of two frequencies are mixed in a nonlinear crystal, resulting in the generation of a third color with their sum or difference frequency. Owing to lack of phase matching between the propagating waves, these processes are typically very sensitive, and tuning mechanisms are needed to support efficient frequency conversion. Usually there is a tradeoff between the bandwidth response and the conversion efficiency, since simultaneous phase matching of a broad frequency range is hard to achieve.

Here we show that the problem of frequency conversion of the SFG process in the undepleted pump approximation, can be mathematically formulated and geometrically visualized in complete analogy with the physics of two-level system, as pioneered by Bloch and Feynman in NMR and atomic physics [1]. In this realm, two coupled linear equations are obtained, relating the evolution of the complex valued amplitudes of the signal and idler. It is also shown that a real three dimensional vector equation can explore the dynamics of the problem, and that any z-dependent phase-mismatch function would lead to a trajectory on the surface of an upconversion Bloch sphere. This pictorial representation enables one to gain physical insight on the evolution of the SFG process along the propagation, and can be extremely helpful in cases where no analytical or approximate solutions exist.

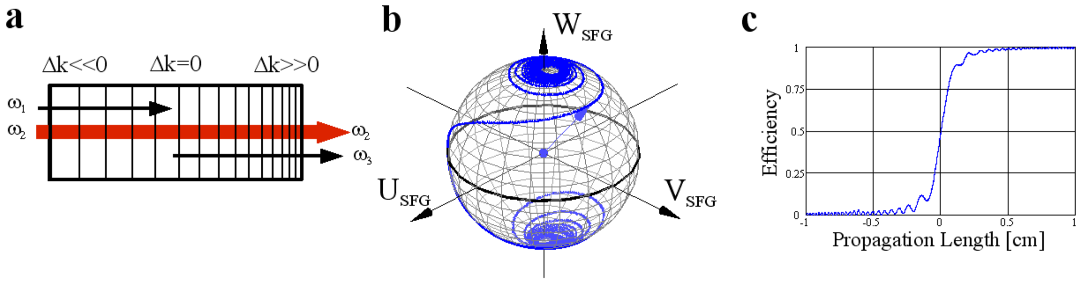

Fig 1. Adiabatic conversion scheme of SFG in the undepleted pump approximation. a) Continuous adiabatic variation of the phase mismatch parameter is required. b) The adiabatic following trajectory, where the state vector initially points at of the south pole, and ends up at the vicinity of the north pole. c) The projection of the trajectory onto the W axis yields the conversion efficiency.

The utility of this analogy is the adoption of the rapid adiabatic passage (RAP) mechanism [2,3], where a strong chirped excitation pulse scans slowly through an atomic resonance to achieve robust full inversion. This adiabatic concept was applied to the context of frequency conversion, and the following adiabatic constraints were derived:

$$\left|\Delta k\right| >> \kappa, \quad \Delta k(z=0)<0 \quad , \quad \Delta k(z=L)>0 \quad , \quad \left|\frac{d\Delta k}{dz}\right| << \frac{\left(\kappa^2+\Delta k^2\right)^{3/2}}{\kappa} \qquad (1)$$

By varying adiabatically the phase mismatch parameter along the propagation axis from a large negative phase mismatch value to a large positive one, we introduce a novel technique, which reconciles the requirements of high efficiency and broad bandwidth. This technique enables one to achieve nearly full color conversion for a bandwidth up to two orders of magnitude wider than in conventional conversion schemes.

2. Experimental Results and Discussion

The adiabatic frequency conversion scheme is realized experimentally using an aperiodically poled KTP device, which was designed to satisfy the constraints posed by Eq. (1). By slowly changing the poling periodicity along the propagation direction, we have achieved high efficient signal-to-idler conversion over a bandwidth of 140nm, and for 100ºC crystal temperature variation, as shown in Fig. 2.

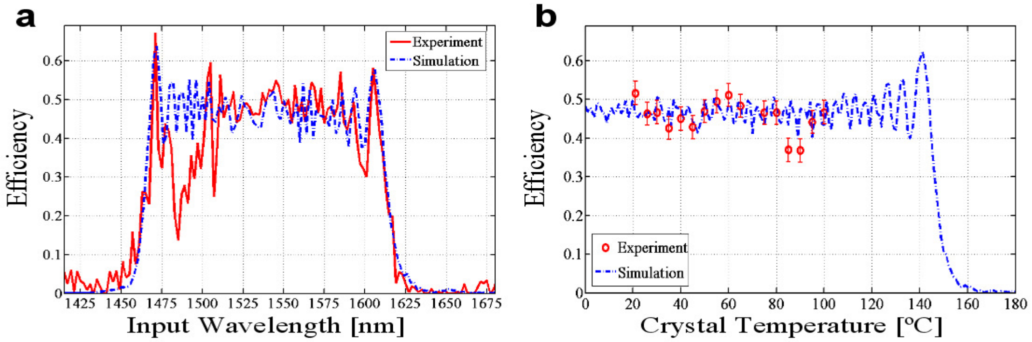

Fig 2. Conversion efficiency as a function of (a) input wavelength and (b) crystal temperature, using the adiabatic aperiodically KTP design at a pump intensity of 15 MW/cm^2.

We also examined the robustness of our design to a variation in the crystal length parameter, where the response for two different crystal lengths of 17 mm and 20 mm was demonstrated (Fig. 3a). In contrary to the conventional conversion process, where one would use a narrow crystal to achieve maximal bandwidth, the achieved bandwidth in the adiabatic design grows as the crystal length increases, while maintaining the same efficiency. The adiabatic sum-frequency converter is also robust to variations in the pump intensity and exhibits broad acceptance angles [4].

Last, this extreme bandwidth response can be tuned to higher or lower wavelengths by changing the temperature of the crystal or by varying the pump frequency [4]. By changing the crystal temperature from to 25^{o}C to 110^{o}C, up to 50 nm bandwidth tunability was observed (Fig. 3b).

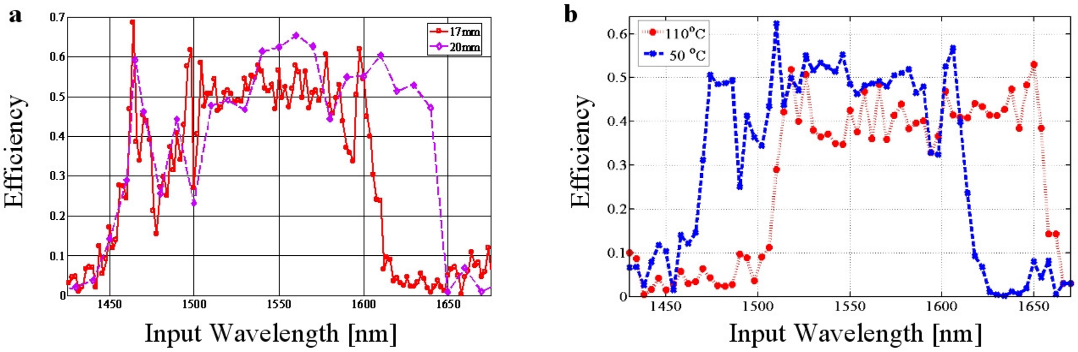

Fig 3. (a) Conversion efficiency as a function input wavelength in two different values of crystal length. (b) Tunability of the ultra broadband response by changing the crystal temperature. In both cases the same adiabatic APPKTP design was used at a pump intensity of 15 MW/cm^2.

3. Conclusion

In this research, we introduced an efficient frequency conversion device for wide range of frequencies. We have characterized its insensitivity and robustness to various process parameters that would usually compromise conversion efficiency, but here, was proven to maintain high efficiency. We believe that the complete analogy of this process with two level physics and its geometrical visualization could bring new physical insights into the process of frequency conversion, and will lead to better understanding of nonlinear optical processes. The present scheme can be utilized to efficient upconversion of broadband fluorescent signals as well as ultrashort pulses.

4. References

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