Optimization of Adiabatic Frequency Conversion

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Introduction

Adiabatic frequency conversion (AFC) is a promising alternative for integrated frequency shifting, unrestricted by the constraints of nonlinear wave mixing. AFC is the process in which light excites an optical cavity, the cavity's index is modulated, and light follows the cavity's instantaneous resonance frequency [1].

We present a theoretical study [2] of the energy efficiency of AFC in an all-pass resonator based on temporal coupled-mode theory. We hope that our study will help move the investigation of AFC from proof-of-principle demonstrations to engineering practical devices for diverse applications.

Efficiency's Upper Limit

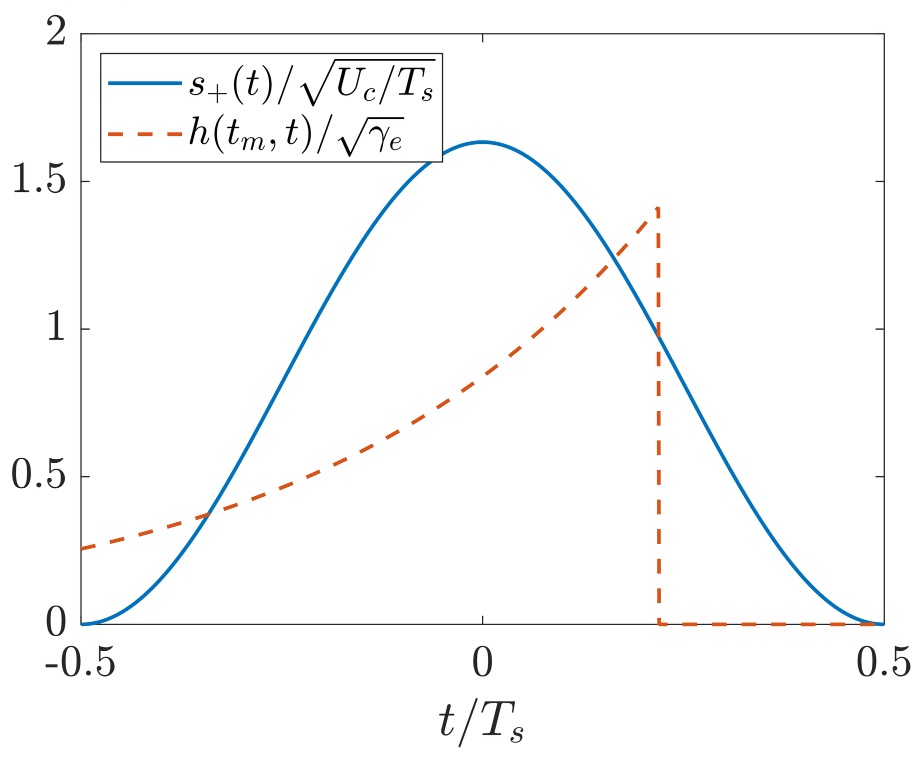
We determine that the AFC energy efficiency η is bounded by the Schwarz inequality as

$$\eta \leq (\gamma_e/\gamma)^2 \left[1 - \exp(-2\gamma T)\right]. \qquad (1)$$

Eq. (1) is independent of the input pulse shape, and is imposed solely by the resonator and modulation scheme.

A corollary of the Schwarz inequality is that Eq. (1) becomes an equality if and only if $s_+(t)$ is proportional to the AFC impulse response $h^*(t_0, t)$. This corollary gives a prescription to optimize η over a set of pulse shapes: maximize the projection of $s+(t)$ along $h^*(t_0, t)$.

Figure 3: Raised-cosine input $s_+(t)$ and input response $h(t_0, t)$ for optimal modulation, yielding the maximum efficiency η of 0.7951.



We explain the shape of $s_+(t)$ for optimal AFC via an argument based on the principles of energy conservation and reversibility.

Funding

The work is supported by the National Science Foundation Grant No. ECCS-1807735. L.C.H. acknowledges financial support from Mexico's National Council of Science and Technology (CONACyT).

References

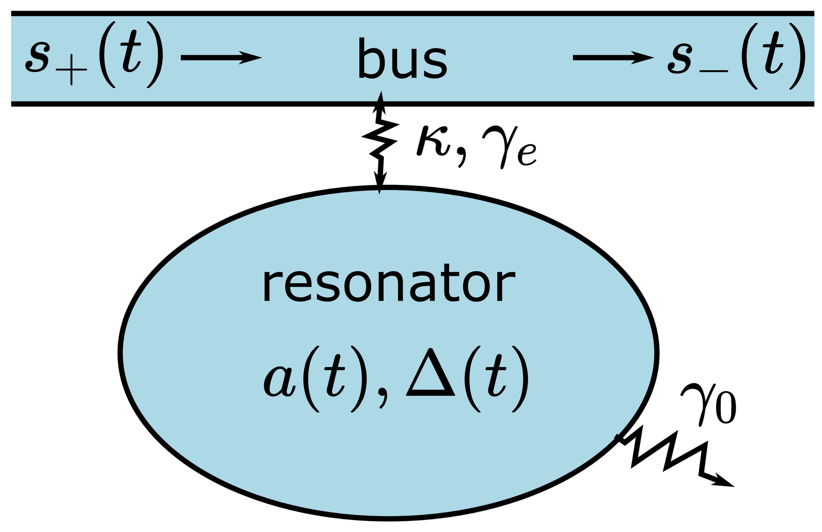
[1] M. Notomi and S. Mitsugi, "Wavelength conversion via dynamic refractive index tuning of a cavity," *Physical Review A*, vol. 73, no. 5, p. 051803, 2006.

[2] L. Cortes-Herrera, X. He, J. Cardenas, and G. P. Agrawal, "Optimization of adiabatic frequency conversion in an all-pass resonator," *Physical Review A*, vol. 106, no. 2, p. 023517, 2022.

Device Configuration and Modulation Scheme

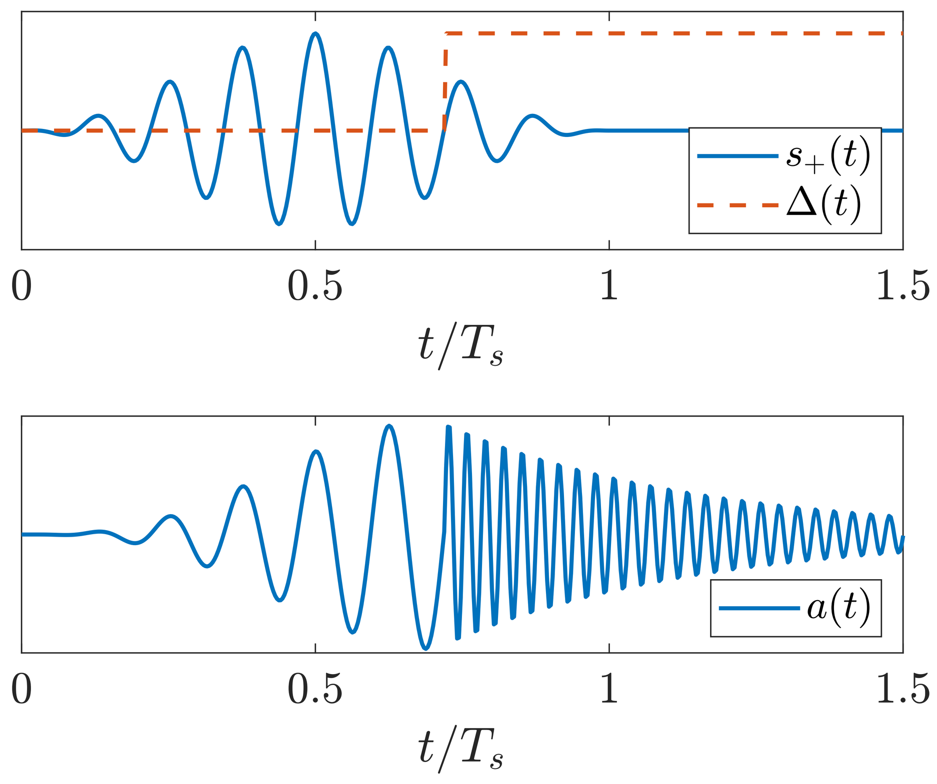
We consider an all-pass resonator (e.g. a ring resonator) under temporal modulation of its refractive index (Fig. 1). The modulation induces a time-dependent detuning $\Delta(t)$ between the input's carrier frequency and the resonator's natural frequency.

Figure 1: Bus-resonator system for AFC. Indicated are the input $s_+(t)$, the output $s_-(t)$, the resonator amplitude $a(t)$, and the instantaneous detuning $\Delta(t)$, the intrinsic dissipation γ_0, the extrinsic dissipation γ_e, and the bus-resonator coupling $\kappa = \sqrt{2\gamma_e}$.



After the cavity undergoes modulation, we expect two things to happen: first, the resonator amplitude $a(t)$ will follow the new frequency; second, the coupling of the input to the resonator will be inhibited. These expectations are accurate when the post-modulation detuning is large compared to the pulse's bandwidth.

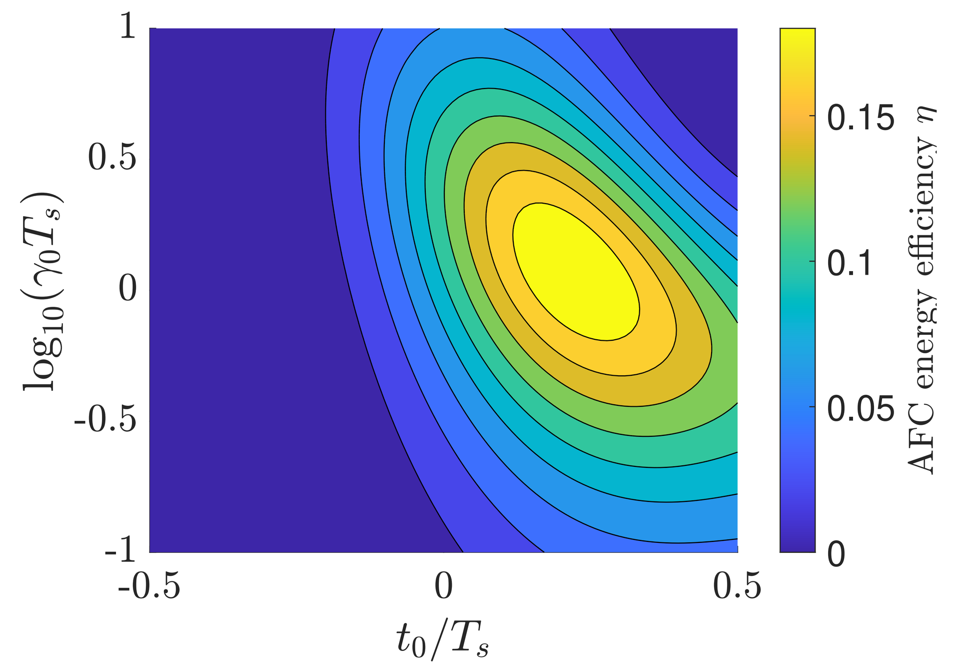
Figure 2: Sketch of signals relevant to AFC in an all-pass resonator: $s_+(t)$, $\Delta(t)$, and $a(t)$. The output $s_-(t)$ is a linear combination of $s_+(t)$ and $a(t)$.



Partial Optimization and Optimal Modulation Time

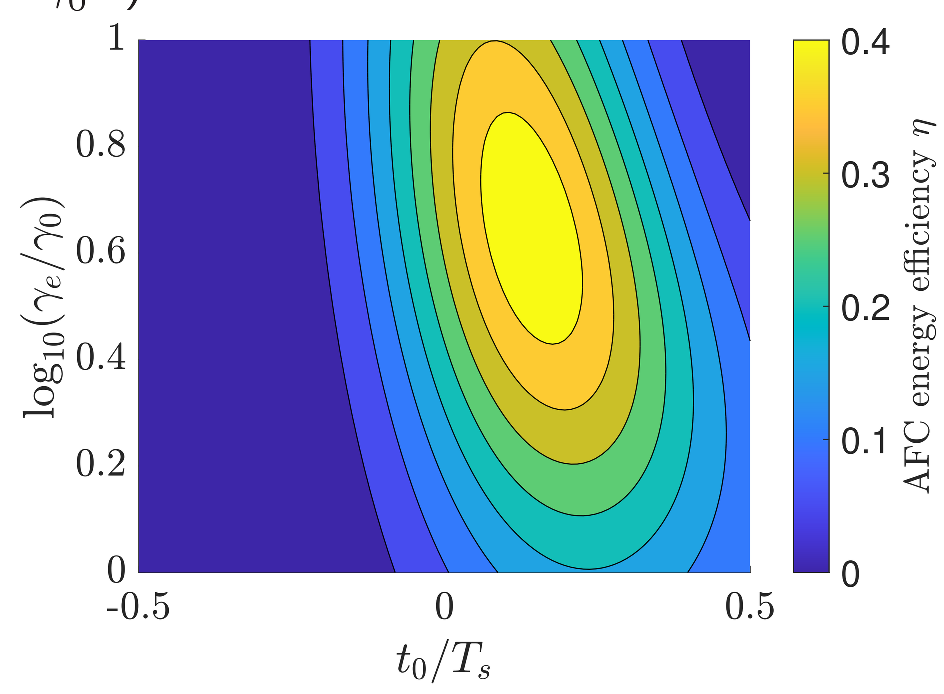
We study AFC with fixed input shape and energy. We consider critical coupling and find that it is suboptimal for AFC (Fig. 4). The optimal modulation time t_0 decreases with increasing pulse width T_s.

Figure 4: Parameter sweep of η for critical coupling ($\gamma_e = \gamma_0$)



We show that when T_s approximates γ_0^{-1}, the resonator must be overcoupled for maximum AFC efficiency (Fig. 5). The optimal modulation time decreases with increasing γ_e. For both Figs. 4 and 5, the decrement in optimal t_0 occurs because the AFC amplitude acts as the output of a low-pass filter.

Figure 5: Parameter sweep of η for fixed pulse width ($T_s = \gamma_0^{-1}$)



Global Optimization and Coupling Asymptotes

We reduce the parameter space by optimizing the efficiency η over the modulation time t_0. As $\gamma_0 T_s \ll 1$, the optimal γ_e converges to

$$\gamma_e T_s = k, \quad k \sim 1. \qquad (2)$$

The value k is determined by maximizing the projection of $s_+(t)$ on $h^*(t_0, t)$.

When $g_0 T_s \sim 1$, the γ_e required to maximize η converges to

$$\gamma_e = 2\gamma_0. \qquad (3)$$

Eq. (3) arises because, when $g_0 T_s \sim 1$, $a(t)$ is approximately proportional to $s_+(t)$ and Eq. (3) maximizes the proportionality coefficient. CW-driven AFC has asymptotes analogous asymptotes.

Figure 6: Global parameter sweep of η for pulsed input

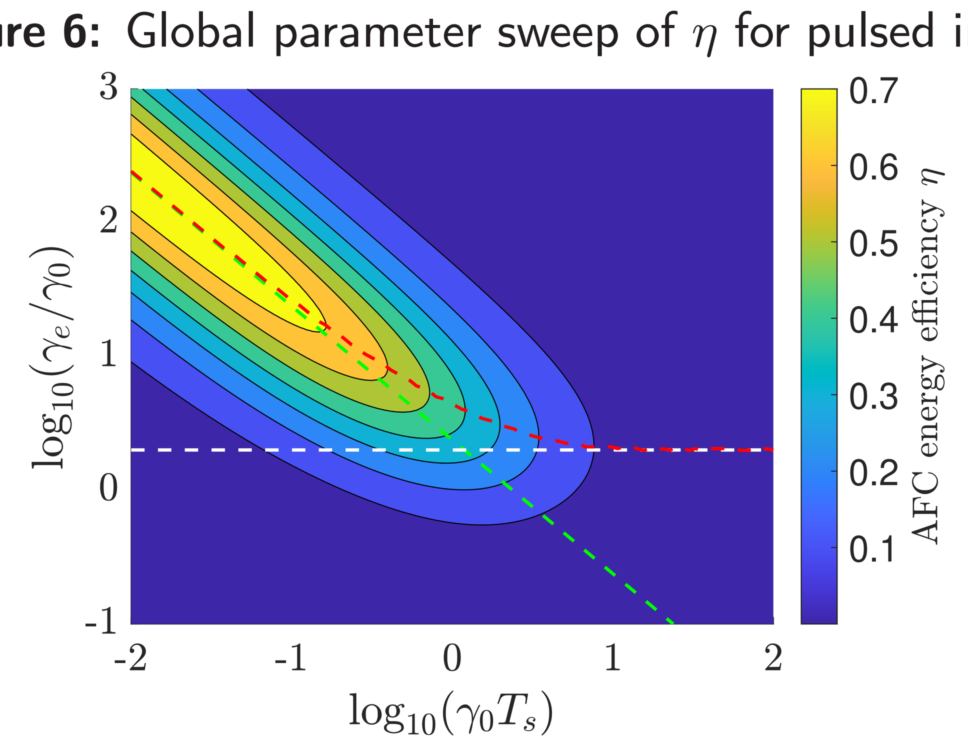


Figure 7: Global parameter sweep of $\eta_{\rm CW}$ for CW input