

# Efficient adiabatic wavelength conversion in Gires–Tournois resonators

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We compare theoretically the performance capabilities of Fabry–Perot and Gires–Tournois resonators when used for adiabatic wavelength conversion. It is shown that the Gires–Tournois device will exhibit superior performance and is able to convert the wavelength of optical pulses with >74% efficiency while nearly preserving their temporal duration. © 2011 Optical Society of America

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Adiabatic wavelength conversion (AWC) is a recently discovered phenomenon that has the potential to be used for reconfigurable wavelength conversion devices in optical communications systems. AWC occurs when the refractive index of a medium is changed in time by an external means while an optical pulse is propagating through it. The resulting frequency shift of the pulse can be understood to occur as a requirement of photon-momentum ( $p = \hbar k$ ) conservation. If the refractive index of the medium ( $n$ ) varies in a spatially uniform manner, then the necessity for the wave number ( $k = n\omega/c$ ) of the optical wave to be conserved implies that its oscillation frequency  $\omega_0$  will shift by an amount  $\Delta\omega \approx -\omega_0 \Delta n/n_0$ , where  $n_0$  is the initial refractive index of the medium.

AWC was first observed to occur in optical resonators [1–3]. It was also argued that the efficiency of the AWC process is inherently limited in optical resonators and that they introduce significant pulse distortion, making them impractical [4]. Instead, the use of slow-light photonic-crystal waveguides was proposed and later demonstrated as an alternative means of confining an optical pulse to a small spatial region for AWC [4,5]. The advantage of this approach is that a waveguide-based AWC device can, in principle, convert 100% of the pulse energy to the new wavelength while imposing negligible distortion. In practice, however, the overall efficiency of these devices may be limited by the notoriously high propagation losses of slow-light modes in photonic crystals [6]. For this reason resonator-based AWC devices may still be a viable alternative to this approach, provided that such devices can be designed to perform efficiently both in principle and in practice. In this Letter we show that, by employing a Gires–Tournois resonator, AWC can, in principle, be realized with > 74% overall conversion efficiency while nearly preserving the temporal duration of optical pulses. We outline the design features that are desirable for such a resonator and present the results of numerical simulations that demonstrate the performance capabilities of such a device.

It was recognized by Notomi and Mitsugi [7], as well as by Preble and Lipson [8], that the efficiency of the AWC of light in a resonator is close to 100% if the photon lifetime of that resonator is sufficiently long; i.e., all light trapped in the cavity at the time of the refractive-index

change will be converted to the new frequency. It was later pointed out that the overall AWC efficiency (the fraction of input pulse energy converted to a new wavelength) is typically much less than this, because not all of the pulse energy will be in the resonator at the time of the refractive-index change [1,4]. If the photon lifetime is much longer than an incident optical pulse, then the optical pulse has a spectrum much broader than the width of the resonance, and it will not couple efficiently into the resonator. In addition to a low AWC efficiency, the pulse will be considerably broadened in the time domain by the spectral filtering imposed by the resonator, potentially removing the information content from an optical bit stream. On the other hand, if the photon lifetime is much shorter than the width of the optical pulse, the AWC efficiency will also be quite low, because much of the pulse energy will have leaked out of the resonator before it has undergone the wavelength conversion.

Therefore, the optimal cavity should have a photon lifetime comparable to the duration of input pulses. Not only will such a cavity maximize the conversion efficiency but it will also preserve the pulses' temporal duration. The photon lifetime can be engineered by adjusting the strength of the coupling of the resonator to external fields. The overall photon lifetime is given by [9]

$$\frac{1}{\tau_{\text{ph}}} = \frac{1}{\tau_{\text{ph}}^i} + \frac{1}{\tau_{\text{ph}}^e}, \quad (1)$$

where  $\tau_{\text{ph}}^e$  is the photon lifetime from coupling alone and  $\tau_{\text{ph}}^i$  accounts for resonator losses from absorption and scattering. It is desirable in practice that such losses be negligible so as to maximize the AWC efficiency. This is the case for an overcoupled resonator, for which  $\tau_{\text{ph}}^e \ll \tau_{\text{ph}}^i$  so that

$$\tau_{\text{ph}} \approx \tau_{\text{ph}}^e. \quad (2)$$

For such a resonator the photon lifetime is determined primarily by the coupling strength, which is an engineerable quantity.

In addition to choosing the optimal photon lifetime, one can use many kinds of optical resonators for AWC,

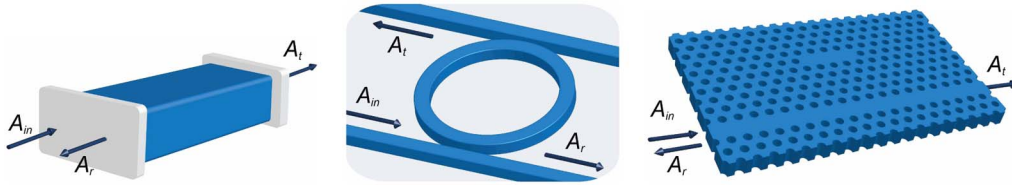


Fig. 1. (Color online) Examples of Fabry-Perot-type resonators.

and we want to know if any of these perform favorably over the others. While many different kinds of resonators exist, they can be grouped into two general classes, referred to here as the Fabry-Perot and Gires-Tournois types. Figures 1 and 2 show three examples of the Fabry-Perot and Gires-Tournois resonator types, respectively. The fundamental difference between them is the number of output ports. The Fabry-Perot-type resonators have two output ports, one a transmission port and the other a reflection port. In contrast, the Gires-Tournois-type resonators have only a reflection port. This fundamental difference leads to significantly different performance when used for AWC.

AWC can be modeled in any kind of dielectric resonator using a theory we have recently developed for describing dynamic refractive-index changes [10]. The AWC process is described by the following equation for the amplitude of a specific cavity mode at frequency  $\omega_q$  that is excited by the input field  $A_{in}(t)$ :

$$[1 + \Gamma(t)] \frac{da}{dt} = -i\omega_q a - \left( \frac{1}{2\tau_{ph}} + \frac{d\Gamma}{dt} \right) a + \kappa A_{in}(t), \quad (3)$$

where  $|a(t)|^2$  is the optical energy stored in the cavity at time  $t$  and  $\kappa$  is the coupling coefficient. The time-dependent parameter  $\Gamma(t)$  describes dynamic refractive-index changes and, in general, depends on the overlap between the cavity mode and the material in which such changes occur. In situations where the index change  $\Delta n(t)$  is spatially uniform,  $\Gamma(t) \approx \Delta n(t)/n_0$  where  $n_0$  is the unperturbed material index. The input field is normalized such that  $|A_{in}|^2$  corresponds to its optical power. It was shown by Haus [9] that the appropriate expression for the reflected field is

$$A_r = -A_{in} + \kappa a. \quad (4)$$

Thus, the output from the reflection port is the result of interference between the resonator's output field and reflected input field. In the case of a Gires-Tournois-type resonator, this is the only field exiting the cavity. For Fabry-Perot-type resonators, there is also a transmitted field given by

$$A_t = \kappa_t a. \quad (5)$$

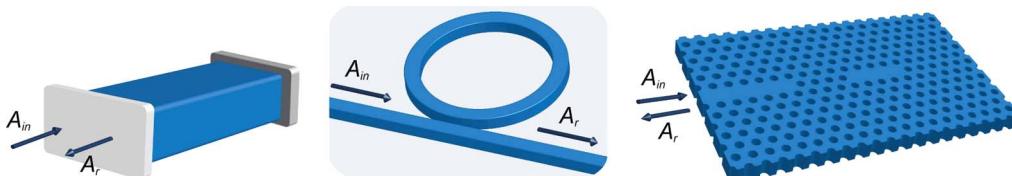


Fig. 2. (Color online) Examples of Gires-Tournois-type resonators.

It can be shown using Eqs. (3) and (5) that the AWC efficiency at the transmission port is maximized for symmetric coupling (i.e., when  $\kappa_t = \kappa$ ), which is assumed in the present Letter. It can also be shown [9] that with this assumption

$$\kappa = (M\tau_{ph}^e)^{-1/2}, \quad (6)$$

where  $M = 1$  or  $2$  corresponds to the number of output ports of the resonator.

To discuss the AWC performance for the two resonator classes, we solve Eq. (3) numerically for an input pulse taken to be Gaussian in shape,

$$A_{in}(t) = e^{-\frac{1}{2}(t/T_0)^2 - i\omega_0 t}. \quad (7)$$

We assume that the cavity is overcoupled and has been engineered so that  $\tau_{ph} = T_0$ , a photon lifetime for which our simulations show the AWC efficiency to be close to maximum for both types of resonators. The input pulse is also assumed to be on resonance so that  $\omega_0 = \omega_q$ . Figure 3 shows output pulse spectra for the two resonator types when the refractive index is reduced by 0.1% over a temporal duration that is 5% of the photon lifetime (see the inset). Here we have initiated the refractive-index change at a time for which the optical energy stored in the cavity is maximum (this time is the same for both resonator types). We assume that the refractive-index change is spatially uniform, and that both resonators have a quality factor of 20,000 ( $Q = \omega_q \tau_{ph}$ ), a typical experimental value [1,2]. The pulse spectra are obtained from their temporal waveforms by taking the Fourier transform,  $\hat{A}(\omega) = \int A(t) \exp(i\omega t) dt$ .

Clearly seen in Fig. 3 is the superior AWC efficiency of a Gires-Tournois resonator. The overall conversion efficiency (defined as the ratio of converted pulse energy in the output port to input-pulse energy) can be calculated by filtering out the original frequency and numerically integrating the remaining spectrum. It was found that the conversion efficiency for the Gires-Tournois resonator is 74.32%, whereas the transmission and reflection ports of a Fabry-Perot resonator each have a conversion efficiency of only 18.58%. That a Fabry-Perot resonator has a lower efficiency is expected, because its output is shared between two ports. However, the efficiency

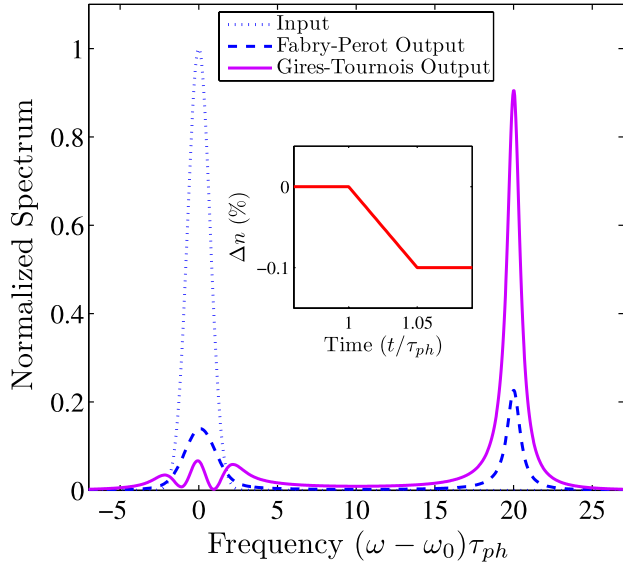


Fig. 3. (Color online) Output spectra for an optical pulse undergoing AWC in two different types of resonators. The dashed and solid curves represent the output spectra in Fabry–Perot and Gires–Tournois resonators, respectively.

is not simply reduced by a factor of 2, as this thinking would suggest, but is reduced by a factor of 4 in this case. The reason for this additional factor of 2 is that, for the same photon lifetime, the strength of the input power-coupling for a Gires–Tournois device must be twice as high as a Fabry–Perot device, and thus twice as much of the pulse’s energy enters into the resonator.

Our simulations show that the efficiency can be further increased by reducing the duration of the refractive-index change or by slightly increasing the photon lifetime relative to the input-pulse duration, but the gain in efficiency is negligible ( $< 0.2\%$ ). This suggests that there is a fundamental limit on the conversion efficiency attainable in resonator-based AWC devices and the device parameters considered here produce results which approach this limit. Different input-pulse shapes may be able to further increase the efficiency, but it is unlikely that such an increase would be significant.

One remaining issue that must be addressed is whether a pulse can maintain its temporal shape after AWC, or if it will undergo significant distortion. Figure 4 shows the input and output pulse shapes in the case of a Gires–Tournois resonator. Shown in this figure are pulse shapes before and after the output pulse has passed through a Gaussian filter to remove a spectral band at the original carrier frequency. If no optical filter is employed, significant oscillations in the pulse power can be seen; these result from beating between the two terms in Eq. (4) oscillating at different frequencies. After the optical filter, the pulse has a smooth shape and a temporal duration that is comparable to that of the input pulse. As expected, it is distorted somewhat in an asymmetric fashion

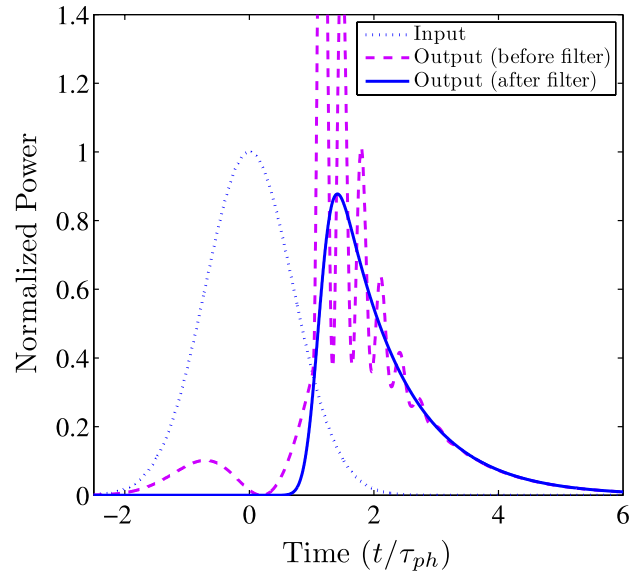


Fig. 4. (Color online) Time-domain output pulse shapes in the case of a Gires–Tournois resonator. The dashed and solid curves show the output pulse before and after passing through a Gaussian filter to remove the spectral peak at the input frequency.

because of the asymmetric exponential response of the resonator.

In summary, we have proposed a device for AWC that operates with  $> 74\%$  efficiency and nearly preserves the temporal duration of optical pulses. The device is an overcoupled Gires–Tournois resonator designed to have a photon lifetime comparable to the input-pulse duration.

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