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Repetition Rate Multiplication by Phase-only Filtering with Multi-cavity Optical Structures

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ABSTRACT:

We propose several all-pass spectrally-periodic optical structures composed of simple optical cavities for the implementation of repetition rate multipliers of periodic pulse train with uniform output train envelope by phase-only filtering, and analyze them in terms of robustness and accuracy.

Key words: Talbot and self-imaging effects, Optical resonators, Pulsed laser, All-optical devices, Ultrafast devices

1.- Introduction

The generation of periodic pulse trains at repetition rates beyond those achievable by mode locking or direct modulation is highly sought after for future ultrahigh-speed optical communication systems. Several strategies for generating periodic pulse trains at repetition rates beyond those achievable by mode locking or direct modulation have been explored. One alternative is pulse repetition rate multiplication (PRRM) of a lower rate source by applying phase-only spectral filtering, usually based on the temporal Talbot effect [1-4].

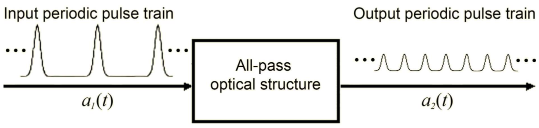

Fig. 1. Architecture of the system. The periodic pulse train is processed by the all-pass optical structure.

We propose and analyze several all-pass spectrally-periodic optical structures of simple optical cavities, concretely ring resonators (RRs), for uniform envelope PRRM.

2.- Theory

The complex envelope of a periodic input pulse train can be expressed as $a_1(t)=a_0(t)\otimes\sum_{n=-\infty}^{\infty}\delta(t-nT)$, where $a_0(t)$ represents the complex envelope of an individual pulse, $\otimes$ is the convolution operator, and T is the temporal period of the signal.

Using the Fourier transform, we can express in spectral domain $A_1(\omega)=\omega_T A_0(\omega)\sum_{m=-\infty}^{\infty}(\omega-m\omega_T)$, where ωT=2π/T, and ω is the base-band angular pulsation, i.e., $\omega=\omega_{\text{opt}}-\omega_0$, ω_{opt} is the optical angular pulsation, ω_0 is the central angular pulsation of the input pulse train. When a spectrally-periodic optical structure of RRs, with an spectral response $H(\omega)=H(\omega+2\pi FSR)$, is applied to the input pulse train $a_1(t)$, we obtain an output pulse train $a_2(t)=\sum_{n=-\infty}^{\infty}C_n a_0(t-nT/N)$, with $\{C_n\}$=IDFT$_n\{H(2\pi m/T)\}$, where FSR is the free spectral range, with $FSR\approx N/T$, N is the desired multiplication factor, IDFT$_n$ denotes the n-th inverse discrete Fourier transform [5], {} denotes a sequence of N elements, C_n are complex coefficients, with $C_n=C_n+N$, and m=1, 2,…, N. We have to impose that all the terms of the sequence $\{|C_n|\}$ have the maximum uniformity for uniform envelope PRRM. Thus, we can define a figure of merit (FM) for PRRM with uniform envelope as $FM=\operatorname{var}\left(\{|C_n|\}\right)/\operatorname{mean}\left(\{|C_n|\}\right)$, where var($\{C_n\}$) and mean ($\{C_n\}$) denote the variance and mean of the sequence, respectively, and the function the optimum is FM=0. The variability of the solution can be estimated with the gradient magnitude $|\nabla FM|$. Both functions, FM and $|\nabla FM|$ must be taken into account in the optimization, indicating accuracy and robustness respectively.

3.- Proposed Optical Structures

The proposed optical structures are composed of one or two proposed basic building blocks, which are showed in Fig. 2, and respectively consist of a single RR, or two identical RRs in cascade or coupled configuration. From the spectral response of a single RR, the spectral responses of cascade and coupled configurations can be obtained, by directly multiplying them in case of cascade configuration, or by using the transfer matrix model method for coupled configuration [6,7]. Each building block can be parameterized with k, a, and ϕ_0, where k is the power coupling factor, $a=\exp(-\alpha L_c/2)$ is the round-trip amplitude transmission factor, α is the power loss coefficient, L_c is the length of the round-trip length, and $\phi(\omega) = \omega_{opt}/FSR = (\omega+\omega_0)/FSR = \omega/FSR + \phi_0$ is the round trip phase, where $\phi_0=\omega_0/FSR$ is the round-trip phase at $\omega_{opt}=\omega_0$. Applying the theory previously exposed, it can be demonstrated that a structure composed of one of the previous building blocks can perform 2x, 3x, and 4x uniform envelope PRRM [2,3]. Table 1 shows the optimum structure parameters set for loss-less filtering (a=1).

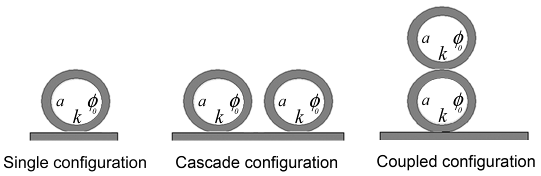

Fig. 2. Basic building blocks of the proposed optical structures for uniform PRRM.

Moreover, by combining the previous optimum building blocks of 2x, 3x, and 4x, we obtain the optical structures showed in Fig. 3, which can perform 6x (2x with 3x building blocks) and 12x (3x with 4x building blocks) uniform envelope PRRM 0. Note that the structures RRs have different sizes, since the building blocks combined have different FSRs. It is worth noting that that required parameters may be a fabrication challenge for current technology, depending on the RRs size required in the concrete application. Thus, RR losses affect significantly to the energy efficiency [8], and it would be desirable to obtain RRs with a>0.95.

Table 1. Summary of the Optimum Building Blocks Parameters Corresponding to 2×, 3×, and 4× Uniform Envelope PRRM.

N	Configuration	k	ϕ_0 [rad]
2	Single	0.8284	1.571
3	Coupled	0.7393	0.8435
3	Cascade	0.8571	0.3335
4	Coupled	0.8284	0
4	Cascade	0.8284	0

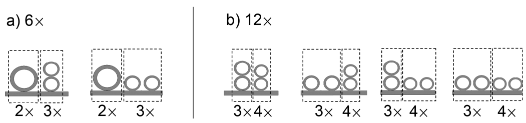

Fig. 3. All-pass optical structures for uniform envelope PRRM for (a) 6× multiplication and (b) 12× multiplication. The basic building blocks are marked with a dashed box.

4.- Conclusion

We have presented a simple method for a uniform envelope PRRM with a high energetic efficiency (ideally 100%, with lossless cavities). We have found that the proposed optical structures can achieve several factors of repetition-rate multiplication (2, 3, 4, 6, and 12).

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