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Removal of CW pedestal from optical signal using nonlinear element in ring laser

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ABSTRACT

We analyze and simulate numerically a bidirectional intracavity field of a ring laser with a $\chi^{(2)}$ nonlinear crystal for sum frequency generation placed within the cavity. Injecting in the nonlinear crystal from one side a beam with a large CW component and a small-amplitude modulation, and from the other side a time-continuous bias beam, we demonstrate numerically that it is possible to reproduce the time-varying portion of the injected light in the circulating modes. This effectively subtracts the CW pedestal from the signal beam. At the same time, the wavelength of the detected light is converted to one that may be more suitable for efficient photo-detection. Our analysis includes rate equations that model two external counter-propagating beams injected in the ring laser cavity and mixed in the nonlinear crystal with the ring laser modes with which they co-propagate.

1. Introduction

Several optical signal processing applications benefit from separating the time-varying, information-carrying optical signal from the time-invariant radiation at the same wavelength. Indeed, a CW offset or pedestal can interfere with optical measurements or data transfer. For example, in optical telecommunications, dispersion-imbalanced nonlinear optical loop mirror (DI-NOLM) proved efficient in pulse compression and CW pedestal rejection [1–3]. CW pedestal suppression is also obtained by pulse compression and spectral broadening in dispersion-compensating fiber, and is important in high-speed optical time-division multiplexing (OTDM) systems [4–6]. However, DI-NOLM requires *a priori* knowledge about the shape of the processed pulse, and sufficient intensity for self-steepening to occur. It also alters the pulse shape. Moreover, the problem of CW pedestal impacts fiber-optic distributed sensing based on the Incoherent Optical Frequency Domain Reflectometry (IOFDR) technique. This is because the range and spatial resolution of the device are limited by the ability of the system to detect weak sinusoidal optical signals at high modulation frequencies imposed on a large portion of CW light [7,8]. Methods based on self-steepening are not applicable here. APDs with limited amplification, in combination with transimpedance amplifiers used to detect these signals, are here limited mostly by the quantum noise [8], which is produced mainly by the time-invariant part of the incoming radiation, i.e., the part not carrying any information. Low signal-to-noise ratio is especially present at high modulation frequencies that are necessary to obtain high resolution of the instrument. Optical detection schemes with a local oscillator (LO) like homodyne or heterodyne detection are utilized to amplify the weak sinusoidal signal, but removal of the unwanted DC is done in the electrical domain. Thus the problem with quantum noise remains, and the signal frequency must be known to choose appropriate LO frequency.

Removal of CW pedestal using $\chi^{(2)}$ nonlinear medium has already been demonstrated [9,10]. Second harmonic generation (SHG) process can suppress small pedestals at the second-harmonic wavelength, which is used for generation of high-quality pulses, but it is not efficient when the pedestal is of comparable intensity as the signal. SHG depends on the square of the intensity, making the response inherently non-linear. Thus, the processed beam is distorted compared to the input beam. A system with two OPOs [10] was also reported to remove CW pedestal by sum-frequency generation (SFG).

In the following, we propose an all-optical system for the extraction of the low-intensity, time-varying portion of electromagnetic radiation imposed on a CW pedestal.

2. Theory and model

The proposed idea is to modulate the effective round-trip loss of two counter-propagating modes of a ring laser by SFG in a $\chi^{(2)}$ nonlinear medium. The setup is shown in Fig. 1.

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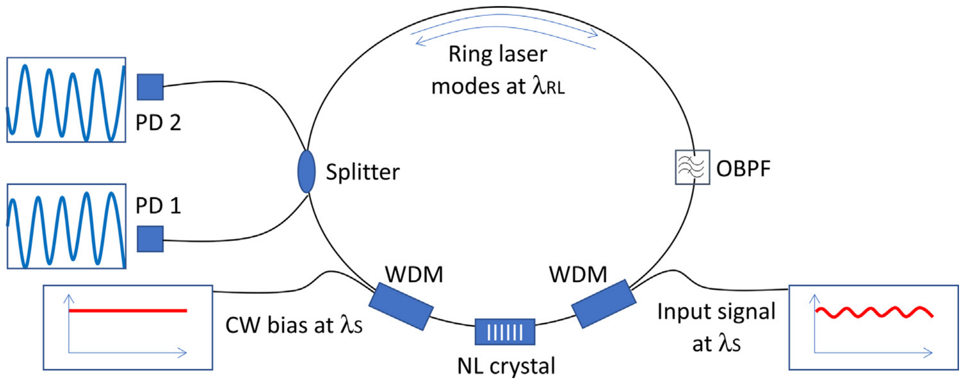

Fig. 1. Ring laser with a nonlinear crystal phase-matched for SFG of the circulating ring laser modes at λ_{RL} and signal/bias beams at λ_S. Input signal has sinusoidal modulation in time. OBPF means optical band-pass filter.

The modes of the ring laser combine through SFG with a signal and a bias beam, which are coupled into the cavity on either side of the nonlinear crystal via dichroic couplers or wavelength division multiplexers (WDM). The ring laser modes are at the wavelength λ_{RL}, while the signal and a bias beam are at the wavelength λ_S. The co-propagating photons at wavelengths λ_{RL} and λ_S for which phase matching condition is fulfilled ($\Delta k = 0$) form a third photon of wavelength λ_{SUM}. Since SFG is a nonlinear elastic process, the conservation of energy dictates that

$$\frac{1}{\lambda_{SUM}} = \frac{1}{\lambda_{RL}} + \frac{1}{\lambda_S} \quad (1)$$

When the photon at λ_{SUM} is generated, one photon at λ_{RL} together with one photon at λ_S are annihilated. This induces parametric loss at λ_{RL} in the direction of the photon at λ_S. Optical band-pass filter (OBPF) tuned to λ_{RL} filters out the possible pump wavelength, and ensures that, once the signal and bias pass the crystal, they do not re-circulate in the ring laser.

The operation of the ring laser is modeled by a rate equation approximation of a two-mode system with no chaotic fluctuations. It is sufficient to model the problem with two coupled equations [11,12] to examine the concept, namely

$$\frac{dI_1}{dt} = \frac{I_1}{\tau_c}(G_1 - \alpha_1 - \delta \cdot I_{Sig} - \beta_1 I_1 - \theta_{12} I_2), \quad (2)$$

$$\frac{dI_2}{dt} = \frac{I_2}{\tau_c}(G_2 - \alpha_2 - \delta \cdot I_{Bias} - \beta_2 I_2 - \theta_{21} I_1). \quad (3)$$

where I_1 and I_2 are the intensities of the clock-wise and counter-clock-wise intra-cavity fields, respectively, G_1 and G_2 are the real (saturated) gain coefficients in the two directions, α_1 and α_2 are fixed round-trip cavity losses including medium attenuation and insertion losses of components, δ is the nonlinear SFG coupling, i.e., the parametric loss parameter, τ_c is the ring laser round-trip time, and β_i and θ_{ij} are respectively the self- and cross saturation coefficients. The intensities of the injected signal and bias beams are I_{sig} and I_{bias}, respectively.

The parametric loss parameter in non-depleted cavity, in perfect phase-matched condition and with Gaussian beams involved is [13]

$$\delta = L^2 2\omega_{RL}\omega_{SUM}\eta^3 d_{eff}^2, \quad (4)$$

where L is the crystal length, ω_{RL} and ω_{SUM} are the angular frequencies of the ring laser and SFG fields respectively, η is the impedance and d_{eff} is the nonlinear coefficient of the second-order nonlinear material. One can express Eqs. (2) and (3) in a simpler way,

$$\frac{dI_1}{dt} = I_1(\alpha_1' - \beta_1 I_1 - \theta_{12} I_2), \quad (5)$$

$$\frac{dI_2}{dt} = I_2(\alpha_2' - \beta_2 I_2 - \theta_{21} I_1). \quad (6)$$

where the gain and combined losses are expressed in parameters α_1' and α_2' for the two modes respectively ($\alpha_i' = G_i - \alpha_i - \delta I_n$), and the round-trip time τ_c is factored into all parameters in the parenthesis. Assuming that the gain is saturated and equal for both circulating modes, and that there are no permanent asymmetric loss elements, the difference between the loss in one and the other direction is

$$\alpha_1' - \alpha_2' = \delta(I_{Signal} - I_{Bias}). \quad (7)$$

Thus, by tuning the bias intensity I_{Bias} to a value close to the average value of signal intensity, only the time-varying part of the signal modulates the intra-cavity field of the ring laser. Thereby, the nonlinear crystal becomes a controlled nonreciprocal component. The ring laser modes become synchronized with signal oscillations. This is then detected by coupling a small fraction of the intra-cavity light out of the ring laser.

3. Results and discussion

Apart from the trivial solution $I_1 = I_2 = 0$ of the Eqs. (5) and (6), there are two possibilities for stable operation, namely unidirectional and bidirectional solution [11]. The coupling coefficient C, defined as $C = \theta_{12}\theta_{21}/\beta_1\beta_2$ determines the regime of operation [11] – for $C < 1$, the bidirectional solution is stable, whereas for $C > 1$, the unidirectional solution is stable, all this assuming the losses are symmetrical for both circulating modes. In the following, the ring laser is assumed to operate in the stable bidirectional regime where counter-propagating modes are fully CW (as region A in [14]). Typical values of $\theta_{12} = \theta_{21} = 0.36\ W^{-1}$ and $\beta_1 = \beta_2 = 0.66\ W^{-1}$ [11] are used together with cavity round-trip time of $\tau_c = 96$ ns, corresponding to a cavity length of around 20 m (in case of optical fiber implementation). Gain in the lasing medium is assumed to be constant $G_1 = G_2 = 0.12$, attenuation and losses are assumed at $\alpha_n = 0.1$. A 10 mm long periodically poled KTP (PPKTP) nonlinear crystal waveguide is placed between entries of the signal and bias beams with instantaneous SFG coupling amplitude of $\delta\ I_{sig} = 0.01$. Measured δ in free-space optical setup [15] was found to be around $0.175\ W^{-1}$ which, assuming realistic mode-area, makes the power of the incident signal in the mW range. Ring laser modes are assumed to be at $\lambda_{RL} = 1550$ nm while the signal and bias are at $\lambda_S = 1510$ nm. The exact phase matching of the beams and the ring laser modes can be achieved by temperature control of the nonlinear crystal, facilitating an efficient SFG process.

Eqs. (5) and (6) are solved using the standard Runge–Kutta method where three distinct regions are modeled – both I_{sig} and I_{bias} constant, I_{sig} modulated with $\omega_1 = 100$ kHz, and I_{sig} modulated