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Multi-state optical flip-flop memory based on ring lasers coupled through the same gain medium

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Abstract

We investigate a system consisting of multiple ring lasers coupled by a single gain medium. All the ring lasers share a common feedback arm. The output power of an individual laser shows periodic oscillations as a function of time. The periodicity of the oscillation is determined by the ratio of the roundtrip times of the feedback arm and the ring cavity. In the case that two of such ring lasers are coupled, either their oscillation periodicities are synchronized, or the system is bi-stable. In the latter operation regime, the system can act as an optical flip-flop memory whose state be switched by injection of external light. The concept can be extended to multi-state operations; an eight-state optical flip-flop memory is experimentally demonstrated.

Keywords: Optical bi-stability; Optical multi-stability; Flip-flop memories; Coupled lasers; Optical feedback; Limit-cycle oscillators; Synchronization; Semiconductor optical amplifiers; Ring laser

1. Introduction

Optical bi-stabilities in laser systems have received much attention shortly after the first laser was invented [1,2] and have been well explored using various types of lasers, such as gas lasers [3,4] solid-state lasers [5] dye lasers [6] and semiconductor lasers [7]. There are several types of optical bi-stability: absorptive bi-stability [1,2,8]; dispersive bi-stability [9]; two-mode bi-stability [10,11] and bi-stability based on symmetrically coupled nonlinear elements [12,13].

Optical flip-flop memories are optical bi-stable elements with optical set and reset operation. Only a few optical flip-flop memory concepts allow extension to multi-state operation. An example is given in [14], which presents a five-state optical flip-flop memory with CW output, containing five cascaded lasers. Extension of such a memory to more states is possible, but the power consumption scales linearly with the extension, since every laser has its own active element.

In this paper, we present a multi-state optical flip-flop memory which contains only one active element. This optical system contains a large number of ring lasers, which are coupled together through a single active element and share one common feedback arm. The output power of any individual ring laser shows periodic oscillation as a function of time. In this sense, each individual ring laser behaves as a limit-cycle oscillator in the context of general nonlinear dynamics [15]. (It should be noted that lasers are traditionally called oscillators, which indicate the oscillation of the electromagnetic field at optical frequency. While the concept of oscillators in this paper means optical systems whose output optical power are not continuous but oscillating.) If a large number of lasers are coupled through the same gain medium, we find that the oscillators tend to synchronize only if the oscillation periodicities are sufficiently close to each other; otherwise, the system exhibits a winner-take-it-all multi-stability. Switching between the

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multiple states can be realized by injecting external light to the cavity so that the system can act as a multi-state optical flip-flop memory.

In this paper, we first discuss the dynamic behavior of a single unidirectional ring laser with incoherent feedback. We show that, depending on the control parameters, in particular the feedback strength, the output of the laser exhibits either periodic (limit-cycle type) oscillations or irregular (chaotic-type) oscillations. The periodicity of the limit-cycle oscillator is determined by the ratio of the roundtrip times of the feedback arm and the ring cavity. After having discussed the physics of a single ring laser with feedback, we will investigate the dynamics of a system that consists of two coupled ring lasers sharing the same active element as well as the same feedback arm. We also show that the two limit-cycle oscillators tends to synchronize if their periodicities are close, otherwise the system is bi-stable.

We investigate the underlying physics of the bi-stability and show that different periodicities of two limit-cycle oscillators would modulate the gain in such a way that the roundtrip conditions for the two ring lasers cannot be simultaneously satisfied. Therefore, depending on the initial power, only one oscillator can be active at a time. Furthermore, it is shown that this principle can be straightforwardly extended to a larger number of oscillators sharing the same gain medium. We give experimental evidence supported by numerical simulations for a system that has eight-stable states. Switching between the states can be realized by injection of external light at the wavelength of the selected cavity.

2. Dynamic behavior of a unidirectional ring laser with incoherent feedback

Fig. 1 shows the schematic of a unidirectional ring laser with incoherent feedback. A semiconductor optical amplifier (SOA) acts as the gain element. The system consists of a ring cavity and a feedback arm. The ring cavity contains an arrayed waveguide grating (AWG) [16], which acts as a filter to select the lasing wavelength, and an optical isolator that allows the light to propagate in only one direction (thus to ensure unidirectional lasing). The mechanical switch in the ring cavity is used to close or open the cavity at demand. A fraction of the lasing light is coupled out of the ring into the feedback arm by a splitter, through which light is reflected back into the SOA from the feedback arm. Note that the feedback light is amplified by the SOA, but it cannot build-up into a lasing state due to the presence of the isolator. The feedback light saturates the gain of the active element and thus influences the lasing light indirectly. Therefore this kind of feedback is called incoherent feedback, in contrast to lasers with conventional optical feedback, in which the feedback light becomes a part of the lasing light when feedback into the laser cavity [17].

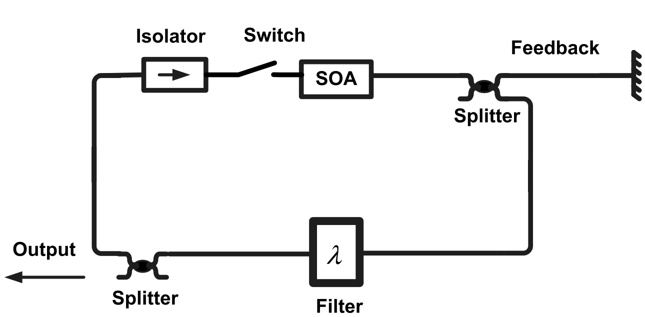

Fig. 1. Schematic of a unidirectional ring laser with feedback. SOA: semiconductor optical amplifier.

The system was built up with fiber-pigtailed components, corresponding to a ring cavity of about 10 m long. A simple roundtrip equation model describing the system depicted in Fig. 1 is presented in Ref. [18]. In the case of such a long ring cavity and without feedback arm, the model predicts irregular intensity. However, the corresponding experimental results show the lasing light in the long ring cavity to converge on a continuous wave (CW). We conjecture that it is due to the optical filter placed in the ring cavity that the instability has been suppressed. Therefore, an optical filter will be included in the model, and this indeed yields the stable CW operation as observed. Another modification with the model presented in Ref. [18] is that in that model the reflection was attributed to an SOA facet. In this paper, we extend the model to account for more general reflections.

The optical filter used in our experiments is an AWG [16], which is a planar lightwave circuit (PLC) with one input and eight output ports, as shown in Fig. 2a. It comprises an input aperture, an arrayed waveguide and an output aperture. When multiplexed optical signals are incident on the input aperture, they are spread by diffraction over the arrayed waveguides. Since adjacent waveguides of the array differ in optical length by a fixed amount ΔL, passing through the arrayed waveguides induces phase differences, in such a way that the focus which occurs at the end of the output aperture at different points depends on the wavelength. Thus signals of distinct wavelengths can be selected by disposing the output waveguides at their respective focal points. The corresponding amplitude response of the filter is shown in Fig. 2b. Therefore, as a simple model in Ref. [19], the output optical field $E(t)$ of the AWG filter at a certain wavelength can be expressed as

$$E(t) = \sum_{j=0}^{7} r_j E(t - \Delta T - j \times \Delta t) \quad (j = 0, 1, \ldots, 7), \tag{1}$$

where j labels the corresponding waveguide (there are eight of them), r_j is the filter coefficient for the waveguide, ΔT is the propagation time for the shortest waveguide, Δt is the propagation time interval corresponding to the length difference (ΔL) of two adjacent waveguides.

Through including the AWG filter and removing the reflection of the SOA's facet, the roundtrip equations derived in Ref. [18] for the laser field formulated at a reference point inside the SOA can now be expressed as