Optical Feedback Regimes Suitable for Distance Measurement with a Ring Laser

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***Abstract*—We numerically study the behavior of a ring laser subject to bidirectional delayed optical feedback, when the isolated laser is in the quasi-unidirectional regime. We find different regimes, two of which are of special interest, because the laser switching period, between the clockwise and the counter-clockwise mode, is linearly related to the time of flight from the laser to one or both remote reflectors. These regimes are thus suitable to implement a telemeter.**

***Keywords*—ring laser, optical feedback, telemetry**

I. Introduction

Ring lasers have been proposed in the last years for different applications [1-5], including gyroscopes, optical flip-flops and clock generators.

The behaviour of ring lasers has been studied both numerically and experimentally [2], finding bidirectional regimes, where both clockwise (CW) and counterclockwise (CCW) modes are active, unidirectional regimes, bistability and chaos.

Recently, we have proposed the application of a ring laser, in the asymmetrical bidirectional regime, to distance measurement [6] with high linearity and accuracy. In the proposed scheme, the laser was subject to delayed optical feedback both from a remote and from a local mirror.

We have now studied in more detail the various regimes taking place for different arm lengths (i.e., for different times of flight from laser to reflectors) to determine the conditions in which the ring laser can be used as a telemeter. We assume in the following that the isolated laser (i.e., the laser without feedback) is in the quasi-unidirectional regime [2].

II. Ring Laser Regimes

The scheme of the ring laser with double feedback is shown in Fig.1.

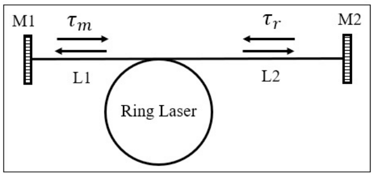

Fig.1 Ring laser subject to double delayed optical feedback

The model we have used in simulations is detailed in [6] and is basically that of Numai [1] with the addition of terms describing the optical feedback:

$$\frac{dS_1}{dt} = [G - \beta S_1 - \theta S_2]S_1 - \frac{S_1}{\tau_{ph}} + \frac{\eta_2}{\tau_{in}} S_2(t - \tau_r)$$

$$\frac{dS_2}{dt} = [G - \beta S_2 - \theta S_1]S_2 - \frac{S_2}{\tau_{ph}} + \frac{\eta_1}{\tau_{in}} S_1(t - \tau_m)$$

$$\frac{dN}{dt} = \frac{J}{ed} - [G - \beta S_1 - \theta S_2]S_1 - [G - \beta S_2 - \theta S_1]S_2 - \frac{N}{\tau_n}$$

In these equations, S_1, S_2 are CW and CCW photon densities, N is the carrier concentration, J is the pump current density, G is the modal gain, θ and β are the (assumed symmetrical) saturation coefficients, and e is the electron charge. Optical injection is modeled by the two terms including η_1, η_2, which account for the total attenuation from the laser to each mirror and back, where τ_{in} is the time of flight in the laser cavity, and τ_r, τ_m are the round trip times from the ring laser to the reflectors and back, i.e., twice the time of flight of each arm.

Using the parameter values of [6], describing a 1 mW laser, and assuming η_1, η_2=0.3, we have found the following regimes, which depend on the arm lengths:

I. An arm is short (<1cm) the other is significantly longer (10 cm to tens of meters): asymmetrical bidirectional regime, i.e., with remarkably different mode amplitudes. The dominant mode is alternatively CW or CCW. Switching between modes takes place periodically, with period $T= 2\tau_m$, i.e, four times the time of flight of the long arm (arm 2 in Fig.1), and $L_2=cT/4$ (c speed of light). This regime (Figs. 2, 3), is described in detail in [6], where its remarkable linearity is reported.

II. Both arms are long (>1cm) and their ratio is in the range 0.1 – 0.25: asymmetrical bidirectional regime. Dynamics is complex and the switching period is nonlinearly related to the times of flight of the two arms.

III. Both arms are long (>1cm) and their ratio is in the range 0.25 – 0.5: the regime is similar to II, but the switching period is approximately the sum of the times of flight of the two arms.

IV. Both arms are long (>1 cm) and their ratio is in the range 0.5 – 2: asymmetrical bidirectional regime, except for $L1=L2$, where the regime is bistable. In both cases, the period is $T=(\tau_r + \tau_m)$, i.e., the sum of the round trip times of both arms (Fig.4) and $L_1+L_2=cT/2$. This regime exhibits an approximately linear behaviour (Fig.5).

V. Both arms are long (>1 cm) but one is much longer that the other (their ratio is outside the range 0.5 – 2): several bidirectional incoming subregimes, where the period T is approximately linearly related to the sum of the rountrip times, i.e.: $T=a\ (\tau_r + \tau_m)$, but with different scale constant a for each specific subregime (Fig.6).

Because of the linear relation holding between the switching period T and the time/times of flight, regimes I (with high accuracy) and IV (with lower accuracy) can be exploited to build a telemeter with the ring laser. This can be done, in practice, by detecting the mode power by a photodiode located behind one (semitrasparent) mirror or by reading the voltage across the laser junction, and then measuring the period T of its square wave modulation, as suggested in [6]. Regime I is suitable for measuring the distance $L_2= cT/4$ of a remote target from the laser output on a long range, which is the typical operating mode of a telemeter. Regime IV instead allows for measuring the distance $L_1+L_2=cT/2$ between two moving reflectors by locating the laser approximately halfway, with a dynamic range of about 50 to 150% of the starting distance.

We observe that regimes I and IV are similar, however different. In regime I the period is twice the roundtrip time of the long arm only. This is the time required for the laser emission to fill and leave the longer arm. After one roundtrip time (i.e., twice the time of flight), the laser switches. The short arm fills almost immediately. However, a new switching does not take place until the light stored in the long arm stops injecting the laser, and this requires another roundtrip time. In regime IV, instead, the period is the sum of the round trip times of both arms, and switching between modes takes place as soon as light travelling one arm reaches the laser, and starts the counter-propagating mode.

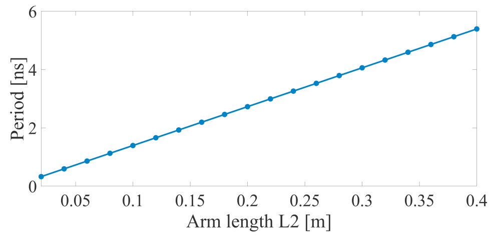

Fig.2 Linearity of Regime I ($L1$= 100 µm)

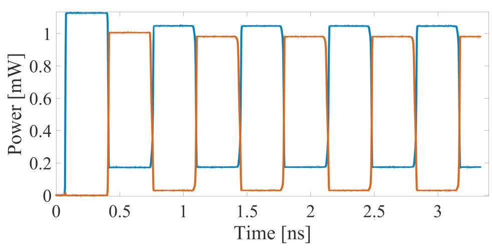

Fig.3 Mode switching in Regime I (L_1=100 µm, L_2=5 cm)

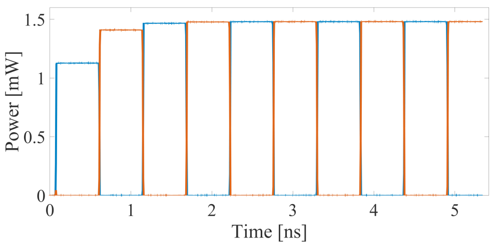

Fig.4 Mode switching in Regime IV ($L1$= $L2$= 8 cm)

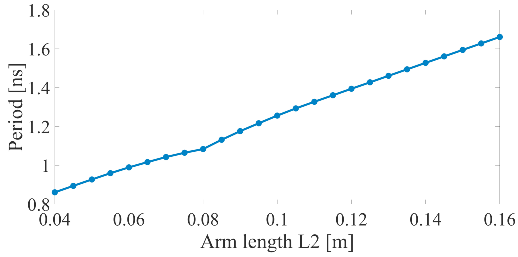

Fig.5 Linearity plot in Regime IV ($L1$=8 cm)

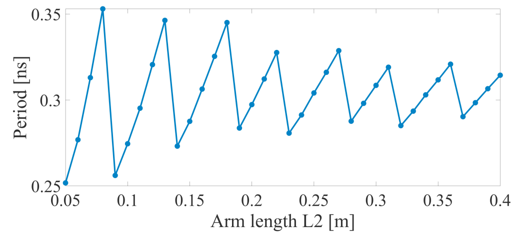

Fig.6 Linearity plot in Regime V ($L1$=2 cm)

This different laser behaviour in different feedback conditions is not surprising, since the strong dependance of the laser regime on the feedback delay has been already observed in standard lasers [7]. Indeed, both regimes have been observed experimentally in ring lasers, though in somewhat different conditions [3-5].

In additon to regimes I and IV, also regimes II, III and V may be considered, in principle, for distance measurement. However, in all these cases the relation of the time of flight with the switching period is less accurate and may change between incoming regimes and subregimes, making this task rather difficult in practice. We would like to point out that the above described regimes, although exemplified in the figures for specific arm lengths, have been found for a variety of arm lengths.

III. Conclusions

By analyzing the regimes of a ring laser subject to optical feedback from two external reflectors, we have found different regimes, two of which are especially suitable for distance measurement.

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