Optik 125 (2014) 3303–3306

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

A novel fiber optic ring-down interferometer for sensing

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ARTICLE INFO

Article history:
Received 3 July 2013
Accepted 18 December 2013

Keywords:
Optical fibers
Sensors
Interference
Coherence

ABSTRACT

A ring-down interferometer (RDI) based on a modified Mach–Zehnder structure by incorporating a pair of mirrors with very high reflectivity into each of its two arms, respectively is proposed in this paper. Launching a coherent light pulse into the interferometer, in each arm, pulse ring-down occurs between its two mirrors and outputs a chain of pulses. The two chains of pulses from the two arms combine and interfere pulse by pulse at the detector and the difference of the light phase between the two arms will be enlarged linearly in proportion to the times of ring-down.

1. Introduction

Optical fiber interferometers have long been investigated for highly sensitive detection of a large quantity of physical parameters owing to the extremely high level of sensitivity [1–3]. The most popular schemes are dual-beam interference configurations, for instance, Mach–Zehnder interferometer (MZI) and Michelson interferometer. Generally, Mach–Zehnder interferometer and Michelson interferometer can be configured with sensitivities better than 10^{-6} rad per square-root hertz [4]. However, one of the fundamental issues for these interferometers is that the sensitivity will vary in a non-linear cosine interference function manner associated with phase difference. Therefore, the tradeoff between sensitivity and dynamic range has to be considered. One method that offers a solution to such a problem is to introduce a piezoelectric fiber structure into one arm to track the phase difference between the two arms at an optimum sensitivity by incorporating a complex electronic serving system. The sensitivity can also be improved by using a longer sensing arm, which in turn limits the dynamic range of the sensor.

In this paper, a novel interferometer based on a ring-down [5–10] Mach–Zehnder structure is proposed and analyzed for the first time, which has a superior sensitivity of 10 mrad level without involving a complex piezoelectric fiber structure [11–13] compared to the conventional Mach–Zehnder or Michelson counterparts.

2. The principle of operation

The configuration of the proposed RID is schematically shown in Fig. 1. A CW (Continuous Wave) light source of a long coherence length is launched into the fiber, then isolated and modulated with an OE modulator in a single pulse format which is then coupled into a specially modified fiber optic MZI, in which a pair of highly reflective mirrors is inserted to form an optical cavity in each arm, respectively.

The input light pulse in each arm bounces back and forth in its own cavities and a very small portion of light is out-coupled each transit cycle, which generates a chain of pulses. The two light pulse chains from the two arms are then coherently recombined at the output of the second coupler and detected by a detector. With the times of bouncing, the phase difference of the corresponding two light pulses from the two arms is linearly enlarged and reflected by the envelope of the electric output signal pulse train with time in coherent cosine shape as shown in Fig. 2.

However, the times of bouncing cannot be increased as will and would be limited by some factors such as the reflectivity of the mirrors, the loss of fibers in the cavities and the sensitivity of the photodetector, which need to be analyzed.

For simplicity, here we consider a balanced RDI consisted of two arms of the same fiber lengths. When a measurand (e.g. strain) that can cause a change in the refractive index or length of fiber is added to the sensing arm, every time after the pulse passes through the sensing arm and the reference arm, a light phase difference of $\Delta\phi_{MZI}$ is introduced:

$$\Delta\phi_{MZI} = \frac{2\pi}{\lambda} nl \left(\frac{\Delta n}{n} + \frac{\Delta l}{l} \right) \tag{1}$$

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http://dx.doi.org/10.1016/j.ijleo.2013.12.060

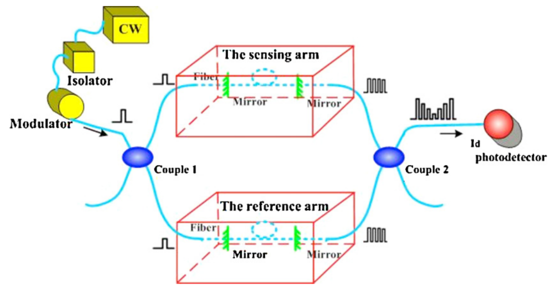

Fig. 1. Schematic diagram of the ring-down interferometer.

where λ is the wavelength of the optical pulse, l is the fiber length in the cavities, n is the fiber refractive index, Δl is the length change caused by a measurand change and Δn is the refractive index change due to the elastic–optic effect arisen from the strain $\varepsilon = \Delta l/l$ with the following relationship [14]:

$$\frac{\Delta n}{n} = \left(\frac{n^2}{2}\right)[p_{12} - \nu(p_{11} + p_{12})]\varepsilon \tag{2}$$

where ν is the Poisson rate, p_{11} and p_{12} are the Pockel's coefficients of the fiber. For a common single mode optical fiber, normally $p_{11} = 0.113$, $p_{12} = 0.252$, $n = 1.482$, $\nu = 0.16$, it infers that $\Delta n/n = -0.22\varepsilon$.

For the mth time reflected corresponding two light pulses, their light distance difference becomes $(n + \Delta n)(m - 1)(\Delta l + l) - n(m - 1)l$ corresponding to a light phase difference $\Delta\phi_{\mathrm{RDI}}(m)$ as:

$$\begin{aligned}\Delta\phi_{\mathrm{RDI}}(m) &= (2m-1)\frac{2\pi}{\lambda}nl\left(\frac{\Delta n}{n} + \frac{\Delta l}{l}\right)\\ &= 0.78 \times \frac{2\pi}{\lambda}(2m-1)n\,\Delta l = (2m-1)\Delta\phi_{\mathrm{MZI}}\end{aligned} \tag{3}$$

It can be seen that the light phase difference of the RDI would be linearly enlarged with the bouncing times m and is $2m$ times larger than that of its conventional MZI counterpart. In practice, the measuring time t is more readily measured than the ring-down times m related with t via $ml = ct/n$. Therefore the light phase difference can also be expressed in terms of measuring time t as $\Delta\phi_{\mathrm{RDI}}(t)$.

$$\Delta\phi_{\mathrm{RDI}}(t) = 0.78 \times \frac{2\pi}{\lambda}\left(\frac{2c/n}{l}t - 1\right)n\Delta l \tag{4}$$

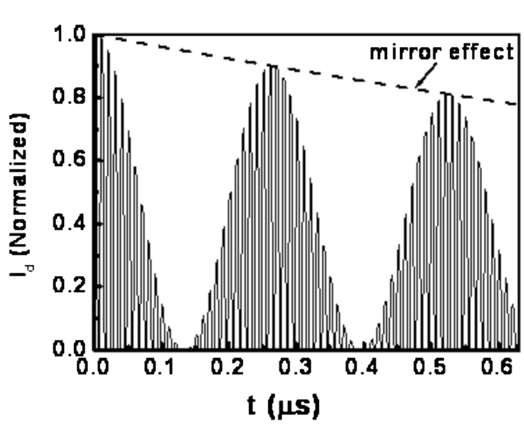

Fig. 2. Output of the detector *Id* vs. *t*.

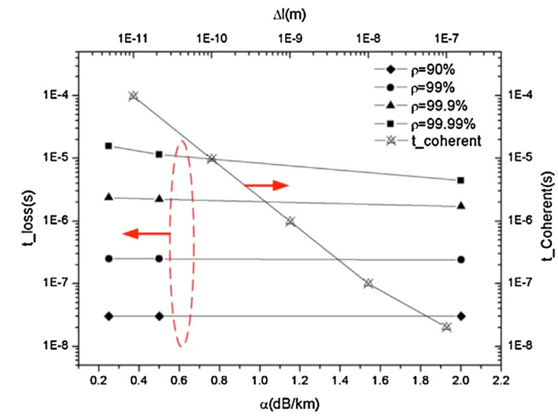

Fig. 3. Comparison of the effects of the fiber loss, mirror reflectivity and the coherent factor.

Thereafter the output signal $I_d(t)$ of the photodetector can also be expressed as [15]

$$\begin{aligned}I_d(t) &= k_0 I_0 k(t)\{1 + \cos[\Delta\phi_{\mathrm{RDI}}(t)]\}\\ &= k_0 I_0 e^{-(2c/n/l/t-1)^{\alpha l}}\rho^{(2c/n/l/t-1)}(1-\rho)^2\left\{1 + \cos\left[0.78 \times \frac{2\pi}{\lambda}\left(\frac{2c/n}{l}t - 1\right)n \times \Delta l\right]\right\}\end{aligned} \tag{5}$$

In Eq. (5), α is the loss coefficient of the optical fiber in dB/km, ρ is the reflectivity of high reflective mirrors, k_0 is the coupling coefficient, I_0 is the input light pulse intensity, and $k(t)$ represents the effects of the fiber loss and mirror reflectivity:

$$k(t) = e^{-(2c/n/l/t-1)\alpha l}\rho^{(2c/n/l/t-1)}(1-\rho)^2 \tag{6}$$

3. Simulation results and analysis

According to the principle described above, simulations for the performance of the proposed RDI are carried out. Fig. 3 shows the normalized pulse coherent feature when assuming that $k_0 = 0.5$; $I_0 = 1$; $\lambda = 1550$ nm; $n = 1.482$; $l = 1$ m. It is revealed that the reflectivity of the mirrors must be high enough to ensure the coherent factor dominant over a long measurement time in order to achieve a largely amplified light phase difference between two arms [16].

For a more quantitative investigation on the effects of fiber loss, mirror reflectivity and the coherent factor on the system, a t_{loss} corresponding to a fixed time when output signal intensity is attenuated to the $1/e$ of its initial value and m corresponding to the times that the pulse was reflected within this period of time are calculated as shown in Fig. 3. Three values of fiber loss coefficient (i.e. 0.25 dB/km, 0.5 dB/km, and 2.0 dB/km) are chosen for simulation, which correspond to a single mode fiber (G658.2) and polarization maintaining optical fiber (SM15-PS-G20A, RCSM15-PS-U17B). In Fig. 3, it is illustrated that it is not necessary to choose mirrors of the highest reflectivity and fiber of the lowest loss for any RDI. There exist sets of optimized groups of mirrors and fibers for a RDI of a given sensitivity. For example, a RDI of a sensitivity $\Delta l = 1$ nm under the dominance of coherent factor can be built up by mirrors of reflectivity 99% and fiber of loss 0.25 dB/km already, which are readily available and of low cost. Only for a system with sensitivity less than 0.1 nm, mirrors of a reflectivity greater than 99.99% are required.

4. Application example

The proposed RDI has many potential applications for measurements of high sensitivity and large dynamic range. Here its