Measurement 58 (2014) 215–220

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Review

Nano force sensing using symmetric double stage micro resonator

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ARTICLE INFO

Article history:
Received 25 May 2014
Received in revised form 9 July 2014
Accepted 6 August 2014
Available online 7 September 2014

Keywords:
Vernier effect
Force sensor
Signal flow graph method
Coupler loss

ABSTRACT

A new approach is proposed to improve a graphical approach with considering intensity coupling loss coefficients in the analytical derivation of the optical transfer functions for a symmetric double stage vertically coupled microring resonator. An optimum transmission coupling condition is determined with considering terms of couplers intensity loss which leads to low insertion loss of 1.2 dB, finesse of 1525, the out of band rejection ratio of 61.8 dB. The resonating system is used as an optical force sensing system to make the benefit of the accuracy of measurements in micro and nano scales. The sensitivity of proposed force sensor in terms of wavelength-shift is 33 nm/nN and the limit of detection is 1.6×10^{-2} nN. The proposed sensing system has the advantages of self-calibration and the low power consumption due to the low intensity.

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1. Introduction

The optical evanescent field sensors have received great interest due to their potential for enhancement of sensitivity, low cost, ultra-compact features [1]. Optical sensors such as surface plasmon resonance sensors [2], Mach–Zehnder interferometer devices [3], and optical grating couplers [4] operate based on the variation in the waveguide effective index. For a ring-based Vernier sensor, small perturbation in waveguide length causes a significant wavelength shift which results in a shift of resonant peaks and provides a ultra-high sensitivity for sensing

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http://dx.doi.org/10.1016/j.measurement.2014.08.044

applications [5,6]. Several analytical methods of signal processing, such as the transfer-matrix–chain-matrix algebraic method [7,8], the scattering matrix method [9] and the signal flow graph (SFG) method [10,11] have been developed for determining optical transfer functions of optical systems.

In this manuscript, the optical transfer function (OTF) with considering the intensity insertion loss of couplers is derived for a resonating system using the Mason's rule [12] with signal flow graph (SFG) method [13] in the Z-domain. The Vernier effect [14,15] is used for symmetric double stage vertically coupled microring resonator which is employed as a nano force sensor. In practice, the proposed system is worked by means of the change of a ring radius due to a load cell or other physical parameters, in which the sensing and reference signals are analyzed, simulated and compared. Based on the signal's wavelength shift, a high sensitive force measurement with the resolution of nano Newton is achieved. Our proposed sensor has the advantages of low cost, self-calibration, the low power consumption due to the low intensity, and can be employed for wide range of force sensing.

2. Effect of coupler loss on OTF

A resonating layout including double stage silicon-on-insulator ring resonator (DRR) with 2 × 2 optical couplers which are vertically coupled together is shown in Fig. 1a. The signal flow graph (SFG) diagram of 2 × 2 optical directional couplers is displayed in Fig. 1b. By taking into account the insertion loss γ and the coupling factor k_i of the ith coupler ($i = 1, 2, 3$ for each coupler), the fraction of light pass through the throughput path is expressed as $C_i = \sqrt{(1-\gamma_i)(1-k_i)}$ and in contrast, the fraction of light pass through the cross path is expressed as $S_i = \sqrt{(1-\gamma_i)k_i}$ [11,16]. The Z-transform parameter or unit delay in Z-domain is defined as $Z^{-1} = \exp(-j2\pi n_{eff}L/\lambda)$ where n_{eff} is the effective refractive index of the waveguide, λ is the signal center wavelength and the perimeter of the ring is $L = 2\pi R$, here R represents the radius of the ring resonator. One roundtrip losses coefficient shown by $X_i = \exp(-\alpha L_i/2)$ where α shows the average ring loss per unit length. Based on the Mason's rule the optical transfer function, H, for an optical device with the input photonics node $E_i(z)$ and the output photonics node $E_n(z)$ is

$$H = \frac{E_n(z)}{E_i(z)} = \frac{1}{\Delta}\sum_{j=1}^{n} T_j\Delta_j \quad (1)$$

where T_j shows the gain of the ith forward path from the input to output port and n is the overall number of onward paths from input to output photonics nodes. The symbol Δ_j considers all of the loops that remain untouched while a signal transverses via each T_j forward path from input to output photonics nodes. The signal flow graph determinant is displayed by Δ, which is given by [17].

$$\Delta = 1 - \sum_{i=1} L_i + \sum_{i\neq j} L_i L_i - \sum_{i\neq j\neq k} L_i L_j L_k + \cdots \quad (2)$$

here L_i is the transmittance gain of the ith loop. The SFG for our proposed system is illustrated in Fig. 1b, in which the input node is $E_1 = E_{in}$ and $E_{12} = E_{drop}$ are considered as the drop node. The Free Spectral Range (FSR) of the device is determined by $FSR = c/n_g, L$ where $n_g = n_{eff} + f_0(dn_{eff}/df)_{f_0}$ is the group refractive index of the ring, n_{eff} is the effective refractive index, and f_0 is the design (center) frequency [5,18]. The FSR of the double stage vertically coupled ring resonator with different radii can be determined by [19,20].

$$FSR_{tot} = N_1 \cdot FSR_1 = N_2 \cdot FSR_2 \quad (3)$$

where N_1 and N_2 are integer resonant mode numbers(RMNs) of each rings which can be determined by the ratio of FSR_{tot} rather than the FSR of each rings (FSR_i). For a choice of equal ring radii, the N_1 and N_2 should have

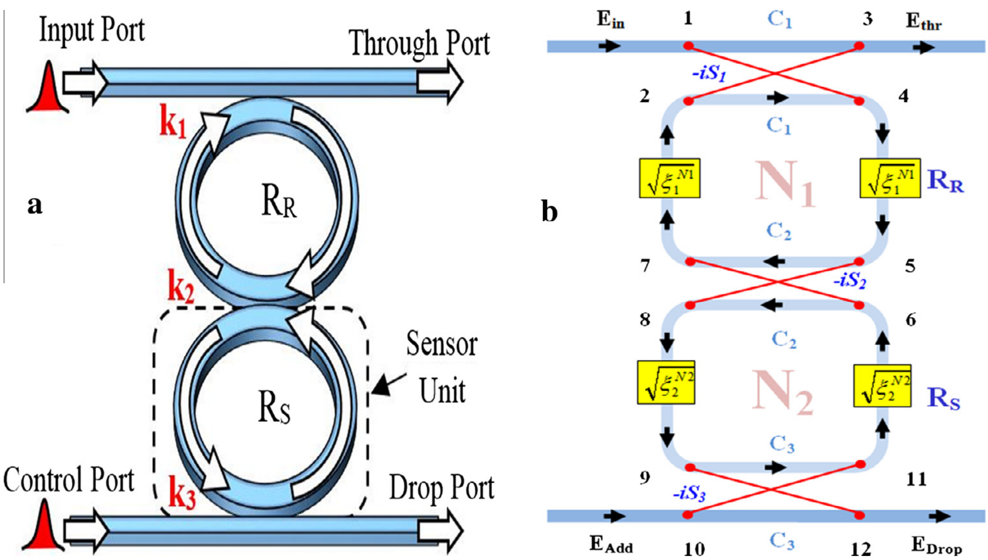

Fig. 1. Microring resonator configuration for micro force sensing. (a) Waveguide layout and (b) Z-transform diagram SFG.