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Semiconductor laser self-mixing micro-vibration measuring technology based on Hilbert transform

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ABSTRACT

A signal-processing synthesizing Wavelet transform and Hilbert transform is employed to measurement of uniform or non-uniform vibrations in self-mixing interferometer on semiconductor laser diode with quantum well. Background noise and fringe inclination are solved by decomposing effect, fringe counting is adopted to automatic determine decomposing level, a couple of exact quadrature signals are produced by Hilbert transform to extract vibration. The tempting potential of real-time measuring micro vibration with high accuracy and wide dynamic response bandwidth using proposed method is proven by both simulation and experiment. Advantages and error sources are presented as well. Main features of proposed semiconductor laser self-mixing interferometer are constant current supply, high resolution, simplest optical path and much higher tolerance to feedback level than existing self-mixing interferometers, which is competitive for non-contact vibration measurement.

1. Introduction

Resonant vibrations of mechanical structure, instruments, sensors and machine tools effect the advanced manufacture process directly. Surface vibration of airplane, the automotive, fast trains, exciter and cantilever beam [1] also need online non-contact monitoring. Hence, the self-alignment, traceable, cost-effective self-mixing interferometer(SMI) [2,3] puts up an irresistible attraction in optical measurement of many fields: micro damping vibration [4], structural analysis [5], medical diagnosis [6] and displacement monitoring [7–9]. SMI with minimal components working under poor reflection condition provides a constant high resolution, which is developed rapidly in last three decades combined with semiconductor laser diode (SL) or linear cavity fiber laser [12]. Till now, SMI is widely used as the laser Doppler velocimetry [10,11], high-precision range finder [13], non-contact measuring instruments for displacement [14], reflectivity [15] and vibration. Have to say, the single-mode SL with a quantum well is a suitable laser source for SMI, which improves the structural simplicity of SMI due to the integrated photodiode for monitoring reflected light [16].

Half wavelength change in SMI optical path generates a 2π phase shift, vibration reconstructed by fringe counting technology obtains an resolution of $\lambda/2$. However, the steadily growing demand in high accuracy announces the $\lambda/2$ resolution is obsolete and outdated. To improve sensitivity of SMI system, many research teams have done significant work to introduce various advanced technologies into SMI. For instance, phase-shifting technique [17,18], sinusoidal frequency modulation (SFM) by current injection, double external cavity(DC) with Fourier transform method reported [19], sinusoidal phase modulation (SPM) by inserting electro optical modulator (EOM) into external cavity [20,22,23], heterodyne technique [21] and electronic frequency down conversion (EFDC) technique [24]. However, these above techniques are not self-reliance. SPM technique improves SMI with EOM requires a broadband high-voltage driver and precise signal generator, the bandwidth of sinusoidal phase modulation limits the measured velocity in a narrow range. Similarly, heterodyne technique is unavailable without frequency shifted feedback laser system and lock-in amplifier. In the meantime, the interpolated FFT calculation used in DC technique is time-costing with a small tolerance of modulation error. EFDC technique replies on multiplier and filter electronics circuits for signal processing as well. The strong dependence on devices makes size of SMI system bigger and more complicated. Since some devices are inserted into optical path, thermal noise and insertion loss increase. Besides, the precious SMI systems achieve satisfying performance only operating at very weak feedback level.

If no variable optical attenuators, the general SMI happens at weak or moderate level in common industrial or scientific environments, solution of which has not been presented by far. Therefore, this paper aims to validate an estimation method for simple SLSMI system operating at wide feedback region, where continuous wavelet transform (CWT) decomposes SMI signal [25]

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to weaken the inclination of fringe, an approximate component is picked and inputted to Hilbert transform for producing exact $\pi/2$ phase shift. Compared with existing SMI and other measuring approaches, CWTHT applying SL not only simplify the structure of conventional SMI, but also provide some advantages: (1) frequency or phase modulation is deleted from SMI, size and cost both decrease sharply, optical path is easy to alignment with absence of inserting devices, besides, maximum velocity of measured vibration is much improved without bandwidth limitation from modulation. (2) Importantly, the feedback level no longer be restricted in very weak feedback level making SMI more applicable in general environments. (3) Furthermore, HT realized on one-dimensional SMI signal takes less time than FFT or windowed FFT and operations on 2/3-dimensional digital image from speckle interferometry, high computational efficiency provides a solid potential possibility in real-time monitoring. (4) Beneficially, CWT is a natural noise-filter in decomposition process. (5) Resolution of $\lambda/20$ in vibration reconstruction is not inferior to phase-shifting method or holography, which validate CWTHT to measure micro-vibrations with arbitrary shapes. In addition, the target physical quantities of SMI measurement can be phase shift, rotating angle of plate, refractive index and thickness or deformation of metal materials as well.

This paper is organized as follows: theoretical mechanism presented in the rationale part contains the theory of SMI, decomposition process and phase extraction at first. Computer simulations at different feedback intensities are plotted to prove the flexibility respectively. Before main error sources being described, comparison with speckle pattern interferometry highlights the advantages of proposed method. Last section gives the experimentation as verification.

2. Theoretical rationale

Self-mixing (SM) is equivalent to a coherent phenomenon between inner optical power and reflected laser beam, phase condition relationship takes below form [26]:

$$\begin{aligned} &\varphi_0(t) - \varphi_F(t) = C\sin(\varphi_F(t) - \arctan(\alpha)) \\ &C = (1-r_2{}^2)r_3\frac{\tau}{\tau_1}\sqrt{1+\alpha^2}/r_2 \\ &\alpha = \frac{\chi}{\rho} \end{aligned} \tag{1}$$

where $\phi_0(t)$ is the initial phase without SM occurrence, the $\phi_F(t)$ stands for variable phase modulated by feedback light due to vibration of external target along optical path. C denotes optical intensity of the reflected light. Line width enhancement factor α denotes an intrinsic index of laser determined by change rate of refractive index χ and stimulated emission gain index ρ of laser medium. r_1, r_2 stands for reflective indexes of two sides of laser internal cavity, r_3 denotes reflective index of vibrating target, τ_1 and τ are propagating time in resonant and external cavities separately. Following the principle of SMI, SM interference happens when the reflected light enters the internal cavity of SL, feedback level changes shape of detected SMI fringes is categorized into four regions: (A) extremely weak level $C \le 0.1$. (B) Weak feedback level $0.1 \le C \le 1$ (D) moderate level $1 \le C \le 4$. (E) High feedback level $C \le 4$.

In region A, optical power of SM coherent process without multi-reflection is written as:

$$p(t) = p_o(t)\left[1 + \mathrm{mcos}\left(2\pi f_L t + 2_{TTf_D}\mathrm{t}\right)\right] \tag{2a}$$

$$\varphi_F = 2_{TTf_D}t \tag{2b}$$

where f_L is the terahertz laser frequency, f_D is frequency shift by Doppler effect .$P_0(t)$ denotes the unperturbed laser power, m denotes undulation index of optical power, $P(t)$ is the variable SM optical power, ϕ_F is phase modulated by SMI process and is equal to initial phase $\phi_0(t)$ in region A. Therefore, modulated phase is proportional to the measured vibration:

$$\phi_F = \frac{4\pi\Delta L}{\lambda} \tag{3a}$$

$$P(t) = P_0(t)\left[1 + \mathrm{mcos}(2\pi f_D t)\right] \tag{3b}$$

where ΔL denotes measured vibration, λ denotes vacuum laser wavelength. Since the $2\pi f_L t$ exceeds response bandwidth of photo detector and is undetectable in SMI system, the shape of SM power of Eq. (3b) represents a cosine curve. Hence, windowed FFT and phase shifting technique are applied in region A for measurement.

In region B, fringe inclination phenomenon emerging from SMI process is proven to be useful because direction of inclination is in accordance with that of vibration, which is used to discriminate the vibration direction. The formula for SMI signal in region B should take the complete phase condition into account, the detectable power is rewritten:

$$p(t) = p_o(t)\left[1 + \mathrm{mcos}\left(2\pi f_o t - \mathrm{Csin}\left(2\pi f_F t - \arctan(\alpha)\right)\right)\right] \tag{4}$$

where f_0 denotes frequency of initial phase $\phi_0(t)$, f_F denotes that of modulated phase ϕ_F. Eq. (4) means shape of SMI power is synthetically decided by two distinct parts: $2\pi f_0 t$ and $C\sin(2\pi f_F \mathrm{t} - \arctan(\alpha))$. From conclusions drawn by precious studies, $C\sin(2\pi f_F \mathrm{t} - \arctan(\alpha))$ plays as a chief factor leading to fringe inclination. The equality of ϕ_F and $\phi_0(t)$ is unable to hold on in region B, the linear relationship with vibration is rewritten:

$$2\pi f_o \mathrm{t} = \frac{4\pi\Delta L}{\lambda} \tag{5}$$

In region D, SMI signal takes same form as region B, The and Eq. (5) is effective as well, but fringe inclination phenomenon become more apparent, waveform of SMI signal presents a saw-tooth curve. Amplitude of $C\sin(2\pi f_F \mathrm{t} - \arctan(\alpha))$ become larger than that of region B because the laser working status is effected by reflected light.

The two parts $C\sin(2\pi f_F \mathrm{t} - \arctan(\alpha))$ and $2\pi f_0 t$ embodies different frequency spectrum distributions and magnitudes, which are depicted using below expressions:

$$F(2\pi \mathrm{f_0}t) << F(\mathrm{Csin}(2\pi \mathrm{f_F}t - \arctan(\alpha))) \tag{6a}$$

$$2\pi f_0 t >> C\sin(2\pi f_F t - \arctan(\alpha)) \tag{6b}$$

The $F(\ldots)$ denotes mean frequency of item in brackets. When external target vibrates at micrometer level, Eq. (6b) shows amplitude of $C\sin(2\pi f_F t - \arctan(\alpha))$ determined by C is much smaller that amplitude of $2\pi f_0 t$,namely, changing speed of $C\sin(2\pi f_F t - \arctan(\alpha))$ is much faster than $2\pi f_0 t$, correspondingly, the frequency bandwidth of $C\sin(2\pi f_F t - \arctan(\alpha))$ is wider and higher than that of $2\pi f_0 t$. Therefore, $2\pi f_0 t$ becomes a relatively narrow-bandwidth component locating at low-frequency zone of SMI frequency spectrum.

We adopt continuous wavelet transform (CWT) to process the SMI signal in region B/D for removing unwanted part $C\sin(2\pi f_F t - \arctan(\alpha))$. The wavelet has its energy concentrated in time domain and employed by wavelet transform for analysis of transients or time-varying signals. Approximate coefficients of each level are: