Optics Communications 393 (2017) 178–184

Contents lists available at ScienceDirect

Optics Communications

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

# Double-path acquisition of pulse wave transit time and heartbeat using self-mixing interferometry

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ARTICLE INFO

*Keywords:*
Self-mixing interferometry
Pulse wave transit time
Non-invasive

ABSTRACT

We present a technique based on self-mixing interferometry for acquiring the pulse wave transit time (PWTT) and heartbeat. A signal processing method based on Continuous Wavelet Transform and Hilbert Transform is applied to extract potentially useful information in the self-mixing interference (SMI) signal, including PWTT and heartbeat. Then, some cardiovascular characteristics of the human body are easily acquired without retrieving the SMI signal by complicated algorithms. Experimentally, the PWTT is measured on the finger and the toe of the human body using double-path self-mixing interferometry. Experimental statistical data show the relation between the PWTT and blood pressure, which can be used to estimate the systolic pressure value by fitting. Moreover, the measured heartbeat shows good agreement with that obtained by a photoplethysmography sensor. The method that we demonstrate, which is based on self-mixing interferometry with significant advantages of simplicity, compactness and non-invasion, effectively illustrates the viability of the SMI technique for measuring other cardiovascular signals.

## 1. Introduction

For the past few years, a variety of non-invasive and non-contact methods for the acquisition of biomedical signals have been developed to increase the quality of patient care [1,2]. Particularly, techniques based on optic sensors are seen as interesting approaches for biomedical signal measuring because of their simple construction, high resolution and low cost. In recent years, more and more studies have been focused on the cardiovascular area, and the arterial pulse wave is the most important signal to be extracted [3]. As is well known, photoplethysmography (PPG) is a popular optical technique for measuring the arterial pulse wave [4].

Over the past several decades, as a new laser technique, self-mixing interference (SMI), which is based on the interaction of a cavity field with the field backscattered from a remote target, has attracted increasing attention. The main advantage of SMI is the simple setup because the whole light path belongs to an interference light path without a reference path. Therefore, the applications of SMI have been popular in many fields, including metrology [5], laser parameter determination [6], terahertz imaging [7], velocimetry [8], thermal expansion [9], tomography [10], and biomedical signals sensing [11,12]. Particularly, SMI-based Doppler methods have been used to measure the cardiac rhythm and the arterial pulse wave [13,14]. Further, K. Meigas et al. [15] measured the pulse wave transit time (PWTT) by the SMI method and compared the results with that by other methods such as PPG, bioimpedance and pulse pressure wave using a piezo-electric transducer. They used a laser diode and electrocardiogram electrode to calculate the PWTT, but this method needs the electrocardiogram signal as a reference and the electrode was in contact with the body. Recently, Arasanz et al. [16] presented a new technique based on SMI for the acquisition and reconstruction of the arterial pulse wave. The cardiovascular pulse as a pressure wave includes changes in the radius of the arterial wall, and such changes may induce a micro-vibration about a few microns over the surface structure which can be captured by a self-mixing interferometer. As a consequence, they improved the classical fringe counting algorithm and discussed the effect of different sampling frequencies on the measured results. However, other cardiovascular information has not been extracted and analyzed.

In this work, we present a technique based on a double-path SMI method for the acquisition of the PWTT and heartbeat. A useful and convenient parameter for continuous monitoring of blood pressure is the PWTT between different regions of the human body [17]. More potentially useful artery pulse wave information has been extracted using a series of signal processing methods based on Continuous Wavelet Transform (CWT) and Hilbert Transform (HT). Therefore, the

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http://dx.doi.org/10.1016/j.optcom.2017.02.052
Received 10 December 2016; Received in revised form 18 February 2017; Accepted 20 February 2017
Available online 23 February 2017
0030-4018/ 

PWTT can be calculated directly with double optical path measurement by simple processing of the SMI signals, rather than by reconstructing the SMI signals with complicated algorithms. The PWTT is known to be correlated with the blood pressure, which can possibly reflect the systolic pressure value by some statistical analysis. In this paper, a typical model is used to analyze the relation between the PWTT and systolic pressure value. Finally, the result of heartbeat measurement is discussed. The SMI method would have a good prospect for medical signal sensing, which can be applied to detect cardiovascular diseases by non-invasive diagnosis.

## 2. Theoretical background

### 2.1. Self-mixing interferometry

The SMI effect has been studied deeply and described in [18,19]. The phenomenon was first characterized by Lang and Kobayashi [20], who analyzed the effects of the external optical feedback in a laser diode. Later models, such as the one presented by Wang et al. [18], use a three-mirror-cavity scheme that also results in the well-known phase equation:

$$\varphi = \varphi_0 - C\sin[\varphi + \arctan(\alpha)] \tag{1}$$

In Eq. (1), $\varphi_0$ and φ are the optical phase of a free-running laser and the optical phase shift of the external path with feedback, respectively. $C$ is the feedback factor and α is the linewidth enhancement factor. Following the principle of SMI, the feedback level is categorized into four regions: (A) extremely weak level with $C \le 0.1$, (B) weak feedback level with $0.1 \le C \le 1$, (C) moderate level with $1 \le C \le 4.6$ and (D) high feedback level with $C \ge 4.6$.

In practice, when light is partially re-injected back into the laser by an external reflector, both the gain and the frequency of the laser will be affected. Hence, the modulated output power of the laser is related to variation of the external optical distance. Based on an analytical steady-state solution, the emitted power $P$ is usually expressed as

$$P = P_0[1 + mF(\varphi)], \tag{2}$$

which is amplitude modulated by a periodic interferometry function $F(\varphi)$ with a phase shift period of 2π. In Eq. (2), $P_0$ is the laser power without optical feedback, $m$ is the modulation index, and φ is the optical phase shift of the external path with feedback, given by $\varphi=2kL=4\pi L/\lambda$ with $k$ being the wave vector, $\lambda$ being the wavelength, and $L$ being the variation of the optical distance from the LD to the reflector. It is recognized that the phase difference is caused by the external optical path difference.

### 2.2. Continuous Wavelet Transform and Hilbert Transform

Because the Fourier basis functions are localized in frequency but not in time, small frequency changes in the Fourier transform will produce changes everywhere in the time domain. Wavelets are located in both the frequency domain and time domain, so different frequencies would be selected in different coefficients of the wavelets. This localization is an advantage in many cases, such as in earthquake wave sensing. The wavelets have their energy concentrated in the time domain and are employed by wavelet transform for analysis of transients or time-varying signals. Compared with Fourier transform, wavelet transform is time-space domain's frequency localization analysis, where through dilation and translation the signal is transformed with multi-scale gradual refinement, and finally the decomposition can adapt to the requirement of time-frequency signal analysis and focuses on arbitrary signal details.

Based on CWT principles [21], the approximate coefficients of each level are expressed as:

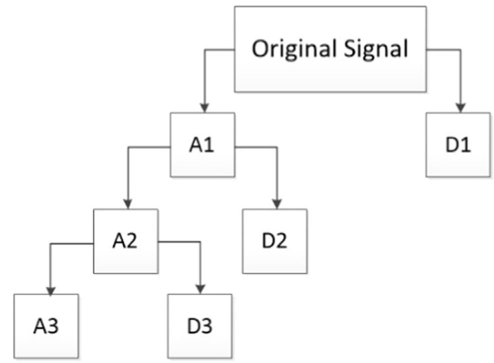


**Fig. 1.** The CWT decomposition process.

$$CWT(\psi, P(t)) = a^{-1/2}\int_{-\infty}^{+\infty} P(t)\overline{\psi}(\frac{t-b}{a})dt. \tag{3}$$

The coefficients CWT ($\psi$, $P(t)$) depict the degree of similarity between the basic wavelet $\psi$ and SMI signal $P(t)$ [22], where $\psi$ stands for different kinds of wavelets: Daubechies, Morlet, Coiflets, Symlets, Haar, Biorthogonal, Hat, Meyer, and so on. $\overline{\psi}$ is the complex conjugate of $\psi$, $a$ is the scaling function, and $b$ is the shifting operator. $a$ describes the time length of one single period basic wavelet, which increases gradually in the decomposition process. As reported in Ref. [22], CWT decomposition is able to extract different frequency components of SMI signals by changing the parameters $a$ and $b$. The specific signal would be reconstructed from the decomposed coefficients in the process. As shown in Fig. 1, the specific signal A1 would be expressed as: A1=A3+D3+D2, and these coefficients denoted different frequency components in the original signal. The processing program can be simulated and computed by a mathematic software, such as MATLAB and LABVIEW. Therefore, CWT is a compatible approach for extracting the medical information of complex cardiovascular signals.

In mathematics and signal processing, Hilbert Transform (HT) is a linear operator that takes a function, $u(t)$, and produces a function, $H[u(t)]$, within the same domain. HT is important in signal processing, where it derives an analytic representation of a signal $u(t)$. This means that the real signal $u(t)$ is extended into the complex plane such that it satisfies the *Cauchy–Riemann* equations. The HT of a signal is given by:

$$H(u(t)) = \frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{u(t)}{t-\tau}d\tau. \tag{4}$$

Eq. (4) interprets HT as a convolution of $u(t)$ with an impulse response function $h(t)=1/\pi t$, which is physically non-existent but can be easily realized by mathematical calculation. The frequency response of the impulse response function takes the following form [23]:

$$H(\omega) = \begin{cases} j, & \omega < 0 \\ 0, & \omega = 0 \\ -j, & \omega > 0 \end{cases}, \tag{5}$$

where $\omega$ is the angular frequency. Eq. (5) implies that the impulse response function introduces a phase shift of $\pi/2$ to signal when $\omega$ is positive, and $-\pi/2$ is otherwise introduced when $\omega$ is negative.

Therefore, HT is known as an ideal digital $\pi/2$ phase shifter, and inputting a cosine function to HT generates a sine function. After the HT using MATLAB, the real signal is transformed to a complex analytical form as:

$$H(u(t))=u(t)+j\hat{u}(t). \tag{6}$$

Specially, the $u(t)$ and $\hat{u}(t)$ are orthogonal in this formula, and therefore, the envelop of the real signal can be denoted as:

$$A(t)=\sqrt{u(t)^2 + \hat{u}(t)^2} \tag{7}$$

This is a useful mathematical processing method that describe the