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Frequency-domain optical imaging with GHz multipixel detection

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Abstract: We present a frequency domain imaging system that allows for two-dimensional detection of phase and amplitude information up to 1 GHz. This is achieved by modulating the gain of an intensifier in front of a CCD camera that is operated in a homodyne mode. The system performance was investigated and characterized by taking measurements on optical tissue phantoms. Furthermore, we determined what modulation frequencies lead to the best signal-to-noise ratio in small tissue geometries, typically encountered in small animal and finger joint imaging.

OCIS codes: (170.3890) Medical optics instrumentation; (170.4580) Optical diagnostics for medicine; (170.5270) Photon density waves

1. Introduction

Frequency-domain optical imaging systems have shown great promise for characterizing blood oxygenation, hemodynamics, and other physiological parameters in human and animal tissues. First clinically useful systems typically employ multiple single detectors [1-4]. The disadvantage of these systems is that for tomographic imaging many single detectors and there detection electronics need to be assembled which can lead to rather large complex, and expensive instruments. More compact charged coupled device (CCD) camera systems, which can record multiple channels at the same time, use gain modulated image intensifiers for detection of light modulation. However, systems presented so far operate only below 150 MHz and need several minutes for data acquisition at one single source position [5,6]. These systems work well for larger media, where the phase shift, even at these low frequencies, is substantial. However, there are many applications that deal with small tissue geometries and small source-detector separations. Examples are small animal imaging and imaging of finger joints. Recent studies have shown that for these cases source-modulation frequencies well beyond 150 MHz can provide much better signal-to-noise ratios (SNR) and hence tomographic image reconstruction results will be improved [7,8].

Here we present a CCD-camera based system that allows for fast acquisition of frequency-domain data in homodyne mode up to 1 GHz. The system was designed with application to finger joint imaging in mind. It was tested regarding frequency-dependent SNR figures and measurement of contrast caused by small perturbations. To test the system for application in joint imaging we have developed a finger phantom.

2. Methods

2.1 Instrument Design: The instrument is designed for fast two-dimensional imaging of modulated light transmitted diffusely through a finger joint. The main components of the system are the illumination part, the detection system, and the modulation sources for light source and detector (Fig. 1). The master signal generator (2023A, Aeroflex Incorporated, Plainview, New York, USA) gives sinusoidal AC input to the laser diode driver that supplies the

Fig. 1. System layout for two-dimensional imaging in the frequency domain.

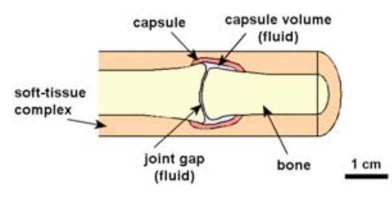

Fig. 2. Scheme of silicone slab phantom with inserted layer (top) and finger joint phantom for simulation of joint diseases (bottom).

laser diode (670 nm, LDH-M-C-670, PicoQuant GmbH, Germany) with bias and AC current. The laser illuminates the surface of the object whereas the axial position is adjusted by moving the laser with a translation stage. The modulated light transmitted through the object is imaged by a lens to an intensified CCD (ICCD) camera (PicoStar HR12, LaVision GmbH, Germany).

The system operates in homodyne mode, i.e. the gain of the ICCD is modulated by a slave signal generator at the same frequency as the laser. A steady state image at the intensifier output is imaged to the CCD. The amount of the signal in every pixel only depends on phase between source and detector modulation. Master and slave signal generators are linked together and phase delay is adjustable. To detect the complete oscillation of the modulation multiple images are taken at phase delays covering the range of 2π and are transferred to a computer. The system is controlled via a graphical user interface. From the stack of images two-dimensional amplitude and phase images are calculated by pixel-wise fast Fourier transform. These relative amplitude and phase images are calibrated in reference to amplitude and phase of the laser spot that is measured directly with light intensity attenuated by neutral density filters only. All images are corrected further on for non-uniformity of the two-dimensional detection system.

The system is intended for tomographic imaging of finger joints in a clinical environment. Therefore, beside high resolution and signal-to-noise ratio, important requirements to meet are an ergonomic and patient friendly hand rest and short data acquisition time.

2.2 Phantom Design: A 2 cm thick slab phantom and a detailed finger phantom were built out of silicone (Fig. 2). We added homogeneously distributed titanium dioxide powder as scattering particles and a special silicone dye (Silopren LSR, GE Bayer Silicones, Germany) to adjust absorption (Table I). To investigate the system sensitivity to perturbations, we inserted a 0.1 cm thin layer of the same material but differing optical properties in the middle of the slab phantom. The layer was bounded by an edge inside the phantom to enable contrast measurement.

The finger phantom simulates healthy joint condition and acute rheumatoid arthritis (RA). In the early stages of RA, changes occur in the optical properties of the capsule, in the fluid in the joint gap and inside the capsule volume [9]. Therefore, bones, a capsule, a surrounding complex which represents the skin and other soft tissue, a joint gap, and a capsule volume were considered in the cylindrical phantom with diameter 2 cm. The joint gap and the volume between capsule and bone were filled with a fluid composed of clear 60% glycerol in aqueous solution for index matching and ink and full milk added to adjust absorbance and scattering.

Table I: Optical Properties of Phantoms

	Slab phantom			Finger phantom					
	Back-ground	Layer 1	Layer 2	skin complex	bone	capsule healthy	capsule inflamed	joint fluid healthy	joint fluid inflamed
Scattering μ_s' (cm^{-1})	10.0	20.0	10.0	10.0	10.0	3.0	6.0	0.04	0.16
Absorption μ_a (cm^{-1})	0.27	0.27	0.54	0.15	0.4	0.8	1.2	0.05	0.13

2.3 Performance Test: The main source of noise is shot noise (quantum noise) and read-out noise of the CCD. Therefore particularly increasing laser optical power, amplification, exposure time, and binning lead to improved SNR. The frequency dependence of the SNR in amplitude and phase images was investigated with the slab phantom far from boundaries and from the edge of the inserted layer. To calculate the SNR, mean and standard deviation of amplitude and phase of the transmitted light were calculated at the source position over an area of 11x11 pixel. Precision was determined from standard deviation of repeated measurements over 30 minutes. Contrast caused by the layer and contrast-to-noise ratio (CNR) was determined too. Contrast was defined as the difference of the signal before and behind the edge and CNR as the contrast divided by the noise. The cylindrical finger phantom with capsule and fluid optical properties of healthy and inflamed RA state was scanned by the laser in the axial center line over a range of 4 cm with images taken every 0.2 cm. From every amplitude and phase image mean and standard deviation at the source position was calculated. In this way a coaxial scan over the joint phantom was extracted.

3. Results and Discussion

The frequency depended SNR at the homogeneous part of a slab phantom in amplitude shows a clear decrease (Fig. 3) whereas DC SNR is nearly independent. In phase images the SNR forms a curve with a maximum around 400 to 600 MHz. Precision in phase is around 1 degree and the relative precision of the amplitude is about 2% to 5%. The contrast caused by the layer in amplitude is decreasing with increasing frequency but with only slight difference between absorbing and scattering layer. The phase contrast has different signs for scattering and absorbing layer and is increasing with increasing frequency (Fig. 4). The CNR for amplitude is decreasing too, but phase CNR shows a clear maximum around 600 MHz.

The scan over the finger phantom shows a general drop in amplitude toward the joint because of the increased diameter of the highly absorbing bone (Fig. 5). Directly at the joint the decreased scattering causes an increase in amplitude and a drop in phase. The two stages of the joint are clearly distinguishable. The time required for a complete data acquisition is about 1.5 s. Thus with regard to use in clinical environment it will be possible to keep total tomographic scanning time below 1 minute.

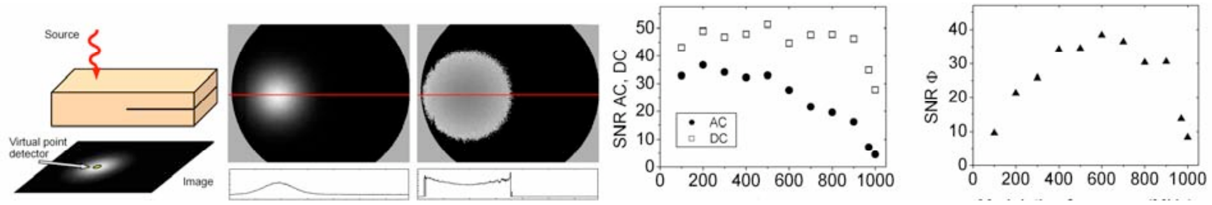

Fig. 3. Signal at homogeneous part of slab phantom, extracting signal at an area (virtual point detector) opposite to the laser position (A), amplitude (B) and phase (C) image of scattered light transmitted through the slab phantom, SNR of amplitude (D) and phase (E) at the virtual detector position depending on the frequency.

Fig. 4. Contrast (difference) of amplitude (A) and phase (B) on slab phantoms caused by layer with enhanced scattering and absorption, contrast-to-noise ratio (CNR) of amplitude (C) and phase signal (D).

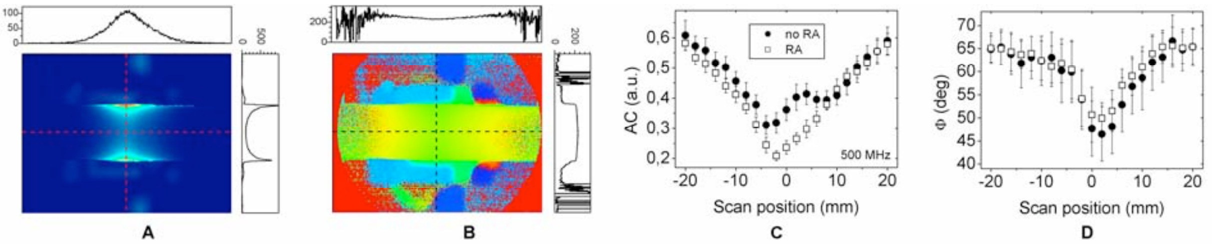

Fig. 5. Scan over the finger phantom at 500 MHz, amplitude (A) and phase (B) image at center source position, for two different stages simulating non-RA and RA coaxial scans were extracted from amplitude and phase images for twenty laser positions, amplitude (C) and phase (D) for 500 MHz, error bars from three times assembling the phantom.

In conclusion the results verify that for evaluation of pathological changes in tissue frequency domain optical imaging can be more valuable compared to continuous wave imaging because the amplitude is very sensitive to changes of the optical properties and phase gives additional information about the type of change. For small geometries and joint like properties the optimal frequency range appears to be around 400 to 600 MHz. The best SNR in phase lies in this range and the SNR in amplitude is still sufficiently large.

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