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# All-optical photoacoustic microscopy

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ABSTRACT

Three-dimensional photoacoustic microscopy (PAM) has gained considerable attention within the biomedical imaging community during the past decade. Detecting laser-induced photoacoustic waves by optical sensing techniques facilitates the idea of all-optical PAM (AOPAM), which is of particular interest as it provides unique advantages for achieving high spatial resolution using miniaturized embodiments of the imaging system. The review presents the technology aspects of optical-sensing techniques for ultrasound detection, such as those based on optical resonators, as well as system developments of all-optical photoacoustic systems including PAM, photoacoustic endoscopy, and multi-modality microscopy. The progress of different AOPAM systems and their representative applications are summarized.

**Contents**

## 1. Introduction

Photoacoustic imaging has drawn considerable attention recently, and is probably the most rapidly-evolving imaging modality in the last decade [1,2]. By utilizing low ultrasonic scattering, photoacoustic imaging provides a powerful tool for imaging deep tissues at spatial resolutions much higher compared with existing optical imaging technologies. There are two major implementations of photoacoustic imaging based on different image formation methods: reconstruction-based photoacoustic computed tomography (PACT) [3,4], and scanning-based photoacoustic microscopy (PAM) [5,6]. In PACT, an expanded laser beam is used to excite the target object as a whole, and an array of ultrasonic detectors, usually arranged in a circular or a planar geometry, is used to simultaneously capture the emitted ultrasonic waves from different orientations. Reconstruction algorithms [7–9] are then employed to generate the initial pressure distribution which can present the optical absorption contrast in the object. Unlike PACT, PAM generates an image based on point-by-point raster scan along the surface of an object. For each laser pulse, a PAM system usually picks one A-line of time-resolved photoacoustic signal. The photoacoustic signal is emitted either from the acoustic focal zone of a focused ultrasound transducer or the optical focal volume defined by a focused laser beam. Based on which method is used to achieve focusing, PAM is either termed as acoustic-resolution PAM (AR-PAM) or optical-resolution PAM (OR-PAM).

Current PAM systems almost exclusively use piezoelectric transducers, often PZT or PVDF based. Piezoelectric transducers usually operate over a band of frequencies centered at their

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resonant frequency when the thickness of the piezoelectric material equals to half of the corresponding wavelength. The axial resolution of both OR-PAM and AR-PAM are highly dependent on the maximum bandwidth for photoacoustic signal detection. Therefore, PAM systems equipped with higher frequency transducers usually offer higher axial resolution and hence better capability of "depth sectioning". Higher frequency transducers, however, require thinner and, therefore, more fragile films, which imposes higher requirements in fabrication technologies. Although a maximal bandwidth of ~120% of central frequency has been demonstrated for piezoelectric transducers [10], a nearly full bandwidth stretched from very low (DC) to very high (hundreds of MHz) is still highly restricted.

As an alternative to conventional piezoelectric transducers, optically-acoustic detectors (acoustic detection based on optical methods) hold promise for achieving PAM with higher axial resolution. The principle advantage of optically-acoustic detectors is the intrinsically broad detection bandwidth. Moreover, optically-acoustic detectors facilitate an innovative "all optical" design where both excitation and detection of photoacoustic signals are realized optically, bringing about the idea of all-optical PAM (AOPAM). In previous developments, besides the ultra-broad receiving bandwidth, many other unique advantages of AOPAM over conventional PAM have been demonstrated, such as high sensitivity [11,12], ease of miniaturization [13–15], and possibility for non-contact measurement [16–18].

In this review article, we first describe the mechanisms and characteristics of two major optical interferometers that both have been employed for AOPAM, including microring resonators and Fabry-Perot (FP) etalons. Next, we present the recent advancement in AOPAM. After that, we introduce photoacoustic endoscopy (PAE) based on AOPAM. Then, the current development of multimodality imaging combined with AOPAM is discussed. At the end, an outlook about AOPAM is described.

## 2. Optical ultrasound detection

Motivated by the need to observe the ultrasonic field, scientists started to examine the feasibility of optical technology for ultrasound detection starting from the 1960s [19]. Afterwards, the development of optical ultrasound detection has made progress gradually benefited in part from the advances in microfabrication technology and material science. In view of the rapid growth of exploration of biomedical photoacoustic imaging during the past decade, researchers also made attempts to investigate the optical methods for detection of photoacoustic signals. Two representative optical ultrasound detection technologies that have been adapted to photoacoustic imaging are polymer microring resonators and FP etalons.

A polymer microring resonator consists of a ring waveguide closely coupled by a bus waveguide, as shown in Fig. 1a. Light is coupled from the bus waveguide into the ring waveguide. A resonance dip in the transmission spectrum occurs, as shown in Fig. 1b, when the round-trip phase acquired by the guided wave is equal to multiples of 2π. That is,

$$(2\pi n_{\mathrm{eff}}/\lambda_c)L = 2\pi m \quad (1)$$

or

$$m\lambda_c = n_{\mathrm{eff}}L, \quad (2)$$

where $n_{\mathrm{eff}}$ is the effective refractive index of the mode guided inside the ring waveguide, L is the circumference of the ring, and $\lambda_c$ and m represent the resonant wavelength and resonance order (an integer), respectively. Acoustic waves deform the waveguide shape and change the refractive index of the waveguide, thereby leading to a shift of the resonance dip. By fixing the probing wavelength at a high slope in the transmission spectrum, incident ultrasonic waves are detected by recording the optical output power. A detailed description of ultrasound detection mechanism can be found in [20]. One of the great advantages in ultrasound detection using the polymer microring resonator is low noise-equivalent pressure (NEP) over a broad bandwidth (e.g. 105 Pa over 350 MHz, and 21 Pa over 70 MHz, as reported by the literatures [12] and [11], respectively). Another advantage of this method is the wide angular response which is made possible by the small element size of the microring [11]. Moreover, the receiving sensitivity of the microring is, to a first approximation, independent of its element size. Compared with conventional piezoelectric transducers, the above-mentioned unique features render the microring an excellent detector for particular PAM applications such as PAE imaging of angiogenesis and multi-scale photoacoustic imaging. Functional measurement

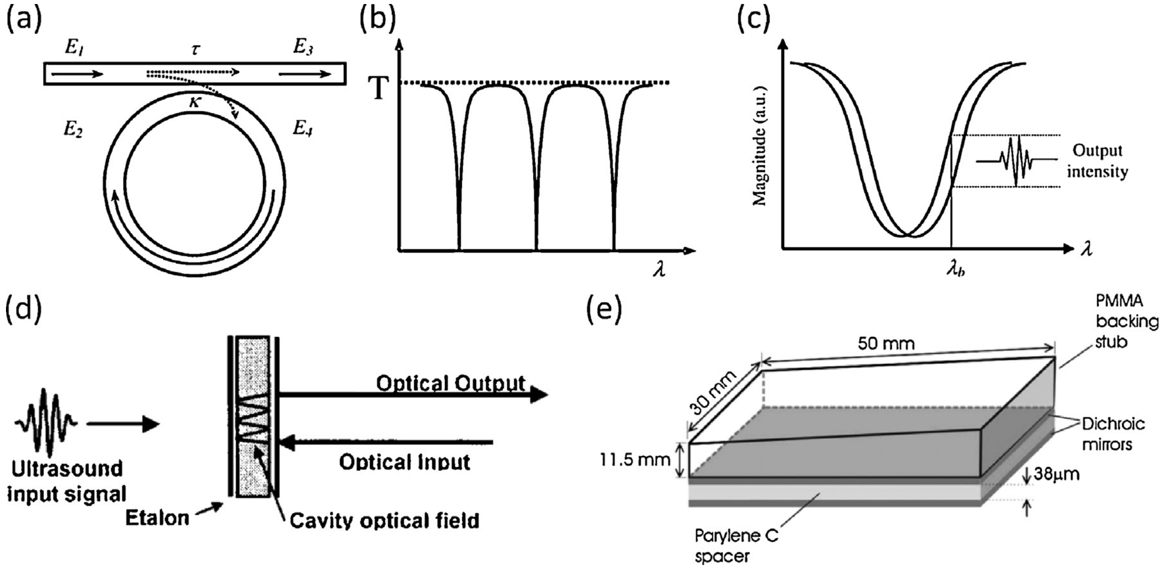

**Fig. 1.** Examples of optical devices for ultrasound detection. (a) A microring resonator consisting of a ring waveguide and a bus waveguide [20]. (b) Typical transmission spectrum of a microring possesses periodic resonant notches [20]. (c) Ultrasound detection using the optical resonance of a microring sensor [20]. (d) An ultrasound input signal induces thickness modulation of a FP etalon which employs a transparent film sandwiched between a pair of mirrors [24]. (e) A FP sensor head for photoacoustic signal detection [26]. Reprinted with permission from Refs. [20,24,26].