

## Phased-array approach to diffuse optical imaging

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### Background

A phased-array method has been previously introduced by Britton Chance's group to better localize optical inclusions in turbid media using frequency-domain optical imaging (Kang *et al.*, 1997). One successful implementation of the method is based on two out-of-phase intensity-modulated light sources, which introduces a null plane (characterized by 0 amplitude and a sharp 0-180 degree phase transition) made by all points equidistant to the two sources (Chance *et al.*, 1993). This method has found applications in areas such as breast imaging (Zhou *et al.*, 1997; Liu *et al.*, 2003) and brain imaging (Chance *et al.*, 1998).

### Three-element linear phased array and enhanced spatial resolution

We propose an extension of this two-element phased-array method that is based on three-element (either three sources or three detectors) linear arrays to collect continuous-wave data and that introduces specific amplitude-phase relationships among the three elements by post-processing of the data. In this case, the null plane of the two-source case is replaced by two null surfaces, as illustrated in Fig. 1. Figure 1 also indicates the amplitude ( $A_i$ ) and phase ( $\alpha_i$ ) factors introduced in the post-processing of the continuous-wave intensity ( $I_i$ ).

This three-element phased-array approach can enhance spatial resolution similarly to a discrete spatial second-derivative of the intensity for a single source-detector system. In fact, the three-element phased-array spatial sensitivity distribution is narrower than for the single source-detector case (see Fig.2, (a) and (b)). Furthermore, Figure 2 ((c) and (d)) shows that the three-element phased-array can achieve depth discrimination because of an asymmetrical sensitivity as a function of depth along the source-detector coordinate (as opposed to

the symmetrical sensitivity in the case of a single source and single detector).

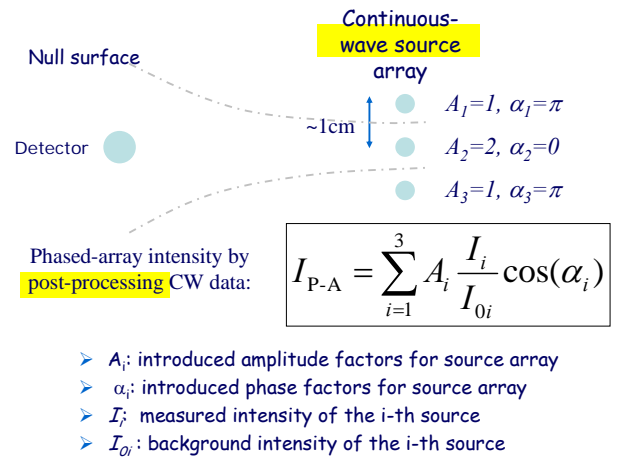


Fig.1. Representative phased-array consisting of three sources with the indicated amplitude and phase factors.

The improvement in spatial resolution is illustrated in Fig 3, which shows linear scans of single-source and phased-array intensities within a turbid medium (milk with black India ink). Two black cylinders were equidistant (3.0 cm) from the source-array and the collection fiber. Figure 2 shows that the two cylinders are not resolved by the single source intensity trace, but are resolved by the phased-array intensity trace with two separate peaks associated with each cylinder.

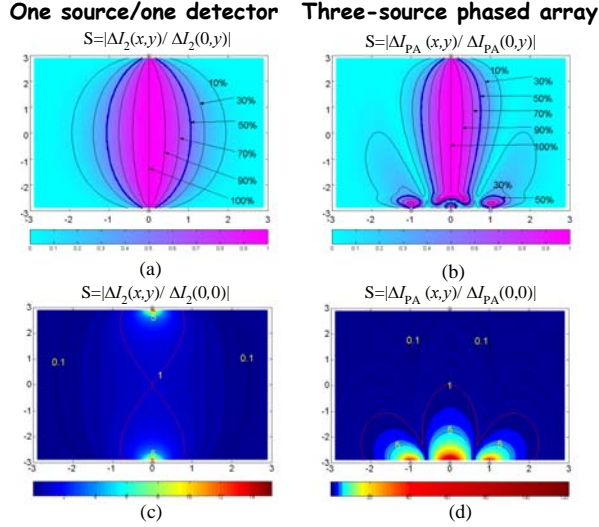


Fig.2. Spatial distribution of the sensitivity function.  $\Delta I(x,y)$  is the change in intensity caused by a small absorbing object of volume  $V$  at position  $(x,y)$ . Panel (a) and (b) show the region of sensitivity of the phased-array intensity is narrower than that of the single-source intensity, suggesting an improvement in spatial resolution. Panel (c) and (d) show the symmetric distribution of the single-source sensitivity function and the non-symmetric distribution of the phased-array sensitivity function, implies a much higher contrast close to the source array than to the detector in phased-array system.

### Two-dimensional phased-array and depth discrimination

Sensitivity to directional structures (such as blood vessels) can be enhanced by combining multiple three-element phased arrays in a two-dimensional array, which consists of a superposition of three linear source-arrays along different directions (see the top view of the planar array in Fig. 4). We have calculated the phased-array intensity associated with each linear array (according to the equation in Fig. 1) and we have taken the maximum of the absolute value of the three phased-array intensities to maximize sensitivity to directional structures. This configuration is illustrated in the experimental setup of Fig. 4, whose depth discrimination capability is shown in Fig. 5. Three absorbing cylinders (color coded as green, red, and blue in the figure) placed at different depths in the medium, can be discriminated by using a two-dimensional source array. In particular, Fig. 5 shows that the single-source intensity is equally sensitive to the top and bottom cylinders, while the intensity from the phased-array-on-top (bottom) is more sensitive to the top (bottom) cylinder.

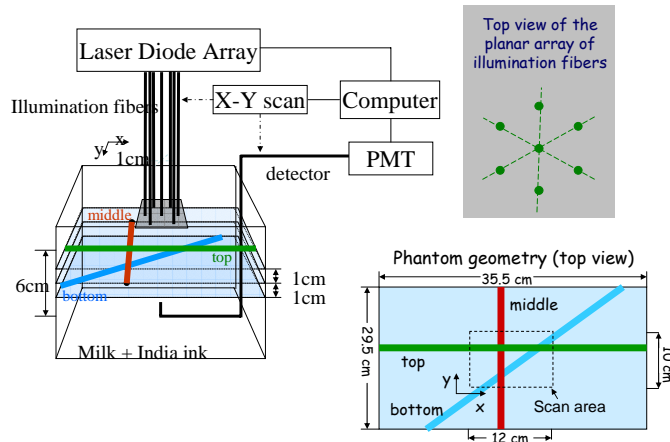


Fig.4. Experimental setup. The seven-element, 2-dimensional source array, the single detector, and the three cylinders embedded at different depths within the highly scattering medium (2% milk, water, and black India ink). PMT: photomultiplier tube. There are three cylinders at different depths along  $z$  axis.

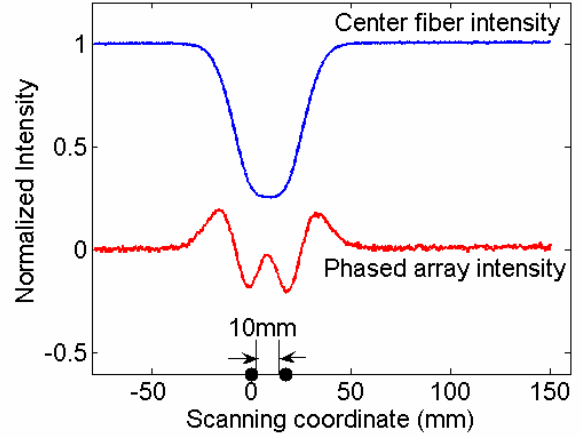


Fig.3. Enhancement in spatial resolution by phased-array intensity. The two absorbing cylinders indicated by the black filled circles (side-to-side separation of 10 mm) are not resolved in the single-source data (center fiber intensity), but are resolved by the two peaks seen in the phased-array intensity data.

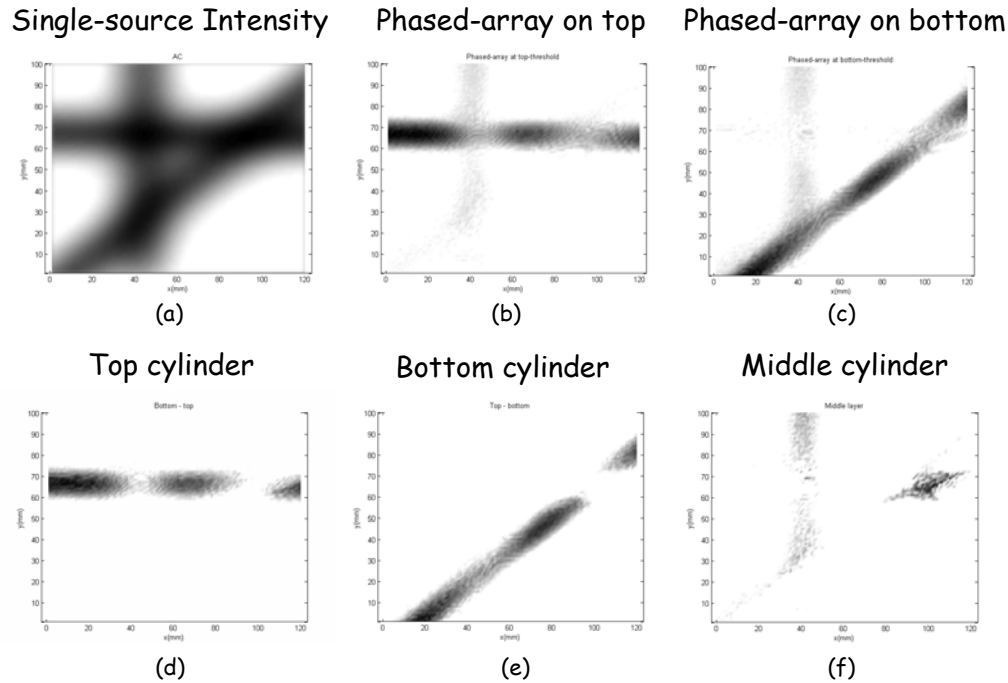


Fig.5. Imaging based on (a) the intensity from the center-source (normalized to the peak value), (b) and (c) the phased-array intensity with the phased-array on top and bottom, (d), (e) and (f) the depth-resolved images.

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