Agile Ultrasound Modulated Optical Tomography Techniques using Smart Fiber-Optics

Nabeel A. Riza and Amana Bokhari

Nuonics, Inc.
3361 Rouse Road, Suite 170, Orlando, FL 32817, USA.
Tel. and Fax: 407-381-1663
email: nabeel@nuonics.com

ABSTRACT

For the first time, proposed is an ultracompact biomedical optical instrument for ultrasound tagged optical tomography that can simultaneously realize an agile ultrasonic probe and an agile optical probe, all in the same fiber-optic package, allowing close proximity in-vivo internal/intracavity imaging. In addition, the same dual probe can be used for external in-vivo imaging of several centimeters thick biological sample. The ultrasound and optical probe utilize the multiwavelength nature of light to provide a compact and fast mechanism to distribute and steer probing beams, thereby reducing motion artifacts and improving image contrast detection sensitivity.

Keywords: Fiber-optics, ultrasound, lasers

1. INTRODUCTION

It is well known that compared with light, ultrasound travels well through deep or several centimeter thick tissue or any highly scattering media. On the other hand, light forms an excellent non-invasive high resolution method for imaging near surface highly scattering biological media. It was proposed in 1989 [1] that ultrasound can be used to tag light with an acoustic frequency, thus enabling the localized detection of diffused light via heterodyne detection methods. Hence, in this way, a focused ultrasound beam can target a zone in the specimen and a beam of light passing through this ultrasound targeted zone can pick up the acoustic vibrations and index modulation from the light scattering centers in the medium. If light is reduced or quenched in a certain region of the tissue, the collected diffused and Doppler shifted light will also suffer a reduction in amplitude of the observed coherent speckle intensity pattern. Thus, by sampling via heterodyne detection in a CCD imager or a photo-multiplier tube with a lock-in amplifier, the optical contrast image information of the probed sample can be recovered. Over the years, a number of groups [2-7] have successfully demonstrated ultrasound modulated optical tomography. All these efforts have used mechanically moving optical and ultrasound beams, leading to slow image generation with high probability of motion-artifacts. It is the goal of this paper to show how agile ultrasound modulated optical tomography can be implemented via a fiber-optic fed wavelength dependent drive probe system that engages both ultrasonic and optical energy.

Over the years, high frequency ultrasound has become particularly attractive for certain intracavity applications, and efforts have been started to realize miniature high frequency ultrasound probes for blood flow and cardiac applications [8-12]. It is clear that as the ultrasonic frequency increases to reduce probe tip aperture size while increasing imaging resolution, the attenuation of ultrasound increases in the biological sample such as tissue. In effect, high frequency (e.g., 20-100 MHz) ultrasound is suited to near field intra-cavity imaging and Doppler flow applications. Realizing

Photons Plus Ultrasound: Imaging and Sensing, edited by
Alexander A. Oraevsky, Lihong V. Wang, Proceedings of SPIE Vol. 5320
(SPIE, Bellingham, WA, 2004) 1605-7422/04/$15 · doi: 10.1117/12.529091

these constraints, this paper looks at realizing an ultracompact dual-mode optical-ultrasonic probe suited for high frequency ultrasound and fine steering optical detection intracavity applications. In effect, the technology in both parts of this paper can be applied across the board to any disease or organ by changing the probe design numbers such as frequency of ultrasonic operation, number of elements in ultrasonic probe, external vs internal ultrasound modulated optical tomography, to name a few parameters. Based on these discussions, the field of biomedical optics can undergo a significant paradigm shift if it is simultaneously possible to provide biologically vital information using these proposed fast and agile dual optical-ultrasonic probes. Because the instrument is generic, compact, and fast, it can be used in a wide variety of commercial applications involving classic ultrasound and optical imaging such as breast cancer tumor detection, cardiac blood flow, and colon studies.

The concept of using simultaneous multiple wavelengths to map spatial two dimensional (2-D) points via a remoted single optical fiber cable probe tip for biomedical applications was proposed, to the best of our knowledge, by N. A. Riza in 1996 [13]. In particular, it was shown how multiple wavelengths can correspond to ultrasonic transducer array elements, providing both signal distribution and signal processing in the wideband optical domain [14-20]. It was also proposed that the probe tips can have dual aperture designs, such as spatially separate transmit and receive apertures for ultrasonic energy.

Hence, for the first time, in this paper, we use and extend some of these original concepts, to realize compact and agile probes for ultrasound modulated optical tomography. The key theme is multiple wavelength signaling and distributed apertures, i.e., optical aperture (transmit and receive) and ultrasonic aperture (transmit). The next section deals with the proposed techniques to achieve these goals.

2. OPTICAL PROBE DESIGNS FOR MULTI-PROBE SPATIAL/SPECTRAL ACCESS

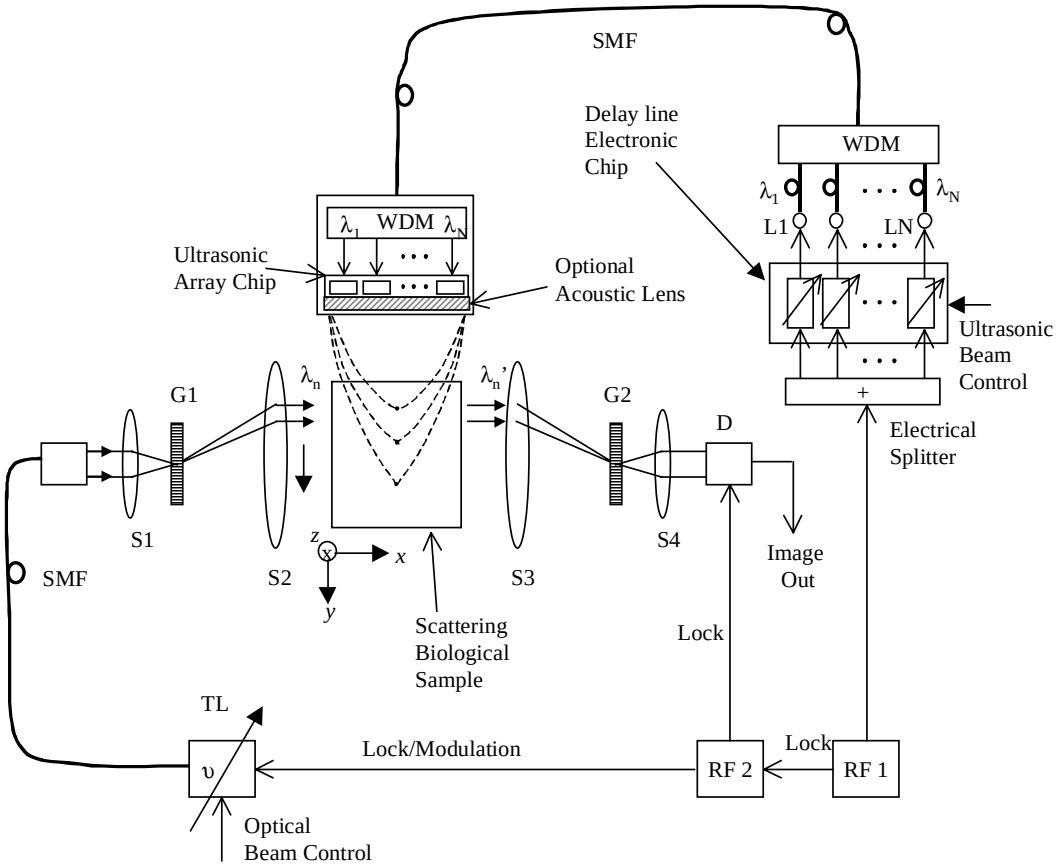

Fig.1 The basic agile external mode operations ultrasound modulated optical tomography system that allows fast ultrasonic and optical tracking of the targeted zone in-vivo biological sample.

Figure 1 shows the proposed agile external mode operations ultrasound modulated optical tomography system that allows fast ultrasonic and optical tracking of the targeted zone in-vivo biological sample. Here a tunable optical source TL such as a laser is used for providing the scanned optical beam with a 1 microsecond/beam scan rate. The overall system operations diagram is shown so as to highlight how optical scanning and ultrasonic feeding technologies can be combined to deliver a powerful high speed agile ultrasound modulated optical tomography system.

Signal source RF1 generates the desired ultrasonic RF drive signal that is first split into N parts with a 1:N RF splitter. This splitter then feeds a N channel electronic delay line chip that can generate desired phase or time delay signals that then modulate the N different wavelength lasers. Hence, by well known ultrasound beam steering techniques, N ultrasonic signals with the right amplitude and phase/time delays can be generated to produce a three dimensional (3-D) ultrasound beam from the frontend probe. An optional acoustic lens can be used at the tip to generate a desired focused beam that is then scanned in 3-D (x, y, z) using the electronic delay chip-based beam controller. All the optical wavelengths are combined in a single optical wavelength division multiplexer (WDM) chip, and the combined light is launched to a single fiber strand that takes the N signals to the ultrasound probe tip package.

On arrival at the tip entry site, the optical wavelengths are separated by a fiber-optic WDM and then each wavelength via fiber or freespace connection is routed on to the correct photosensitive area of the ultrasonic array chip. This chip can be a photo-acoustic material or can be a micromachined or MEMS based ultrasonic array chip with a flip-chip bonded photo-sensor array to convert optical energy from the N wavelengths to RF drive energy for the MEMS ultrasonic transducer N elements. The ultrasonic array chip can also be a standard piezoelectric transducer array

working at a typical 3 MHz frequency. Hence, by simply controlling the RF1 frequency and electronic chip-based delays, the ultrasound beam produced by the fiber remoted frontend tip rapidly (e.g., in 10 microseconds) moves in 3-D in the targeted zone of the biological sample.

Next, to efficiently collect the diffused light from the ultrasound tagged region, the tunable laser TL has its laser wavelength changed to position the scanning beam at the location of the focused ultrasound beam. Light λ_n from the laser is coupled to a fiber GRIN lens, generating a typical 1 mm diameter optical beam that also well matches the resolution possible with MHz range ultrasound. At the exit of this transmit GRIN lens, the lens S1 and grating G1 combine to produce a spatially offset beam along y-direction, where the spatial offset/scan position depends on the given wavelength of the laser [21-28]. The diffused and Doppler shifted λ_n' light from the sample is collected by a lens pair (S3/S4) and grating G2 device before the speckle pattern is captured by the detector D that can be a CCD camera or a photo-multiplier tube (PMT). The CCD/PMT is operated in a lock-in mode via locked source RF2 so as to generate a heterodyne detected signal required for proper speckle processing to generate the desired sample contrast optical image.

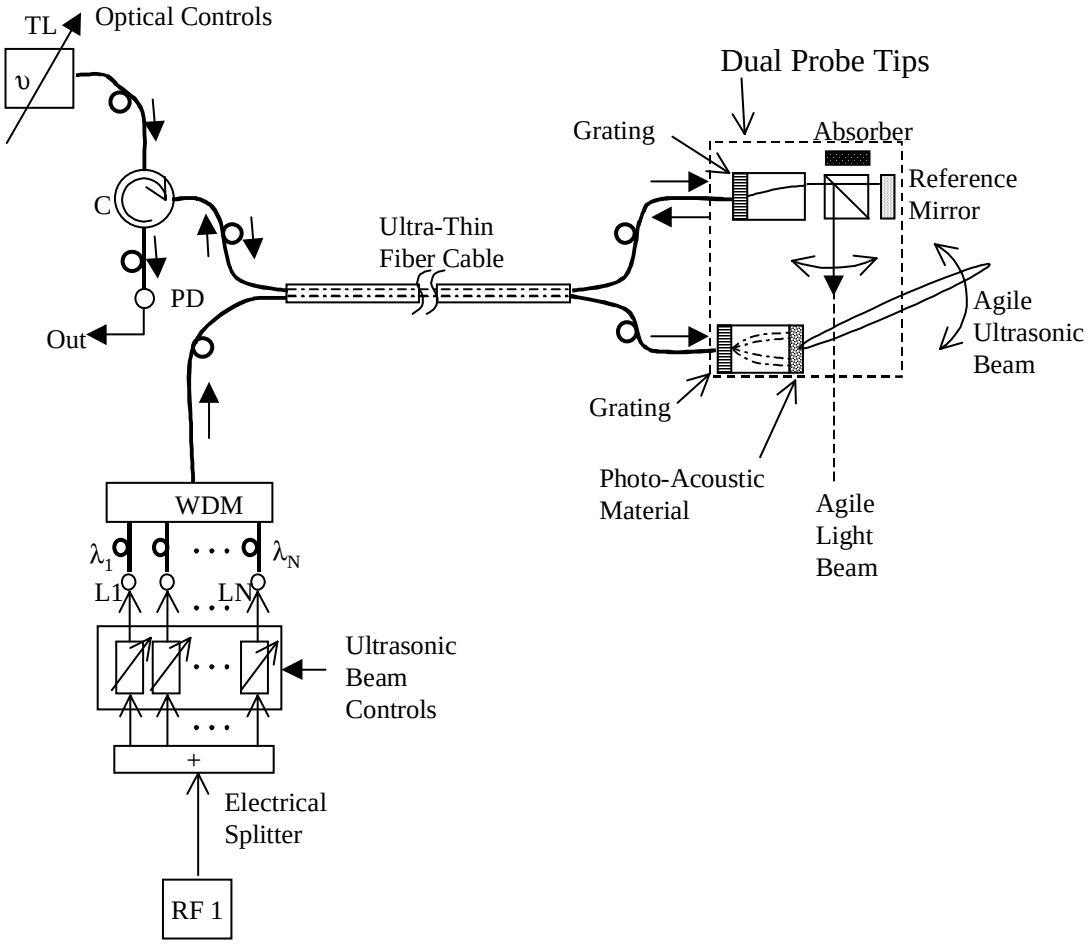

Fig.2 The basic fiber-coupled agile internal/intracavity mode operations ultrasound modulated optical tomography system that allows fast ultrasonic and optical tracking of the targeted zone in-vivo biological sample.

Fig.2 shows the proposed fiber-coupled agile internal/intracavity mode operations ultrasound modulated optical tomography system. The system on the ultrasonic side is similar to Fig.1 The difference lies in the probe tip where a fiber is connected to an ultracompact Grating-GRIN lens-Photoacoustic Material tip. In essence, this tip can be 1-2

mm in diameter with no connecting electrical power, making the tip highly safe from an RF point of view. Because a grating is used in the tip, a linear 1-D scan ultrasound beam is achievable for scanning. Note that the system is Fig.2 uses a fiber cable with two separate fibers. One fiber is for the ultrasonic probe, while the other fiber is used for an optical transmit-receive probe. There are several options for the optical probe, based on whether incoherent or coherent detection is used and whether large aperture multimode fibers or small aperture single mode fibers (SMF) are used. In Fig.2, a coherent optical detection scheme is used so as to implement heterodyne detection using the ultrasound tagged light and a reference light beams returning after retroreflection from the reference mirror in the probe tip.

Note that the optical tip directs the light at 90 degrees to the ultrasound beam. Also, the two tips are physically offset in space so that the optics does not attenuate the ultrasound. A small cube beamsplitter is used in the optical tip to combine the Doppler signal coming from the diffused specular light plus the reference optical beam light from the mirror. On return, this beam pair passes through a fiber optical circulator C and is detected via a photodiode PD that generates the heterodyne signal indicating optical contrast at the probe tip location for a given optical wavelength. This probe design is particularly suited for high frequency ultrasound where RF noise within the intracavity guide and even at the probe tip can be difficult to handle and minimize.

3. CONCLUSION

In conclusion, the features of the proposed dual ultrasound/optical probe system are:

- High Speed
  The ability to steer and focus an ultrasound beam rapidly and in synchronization with a steered optical beam makes ultrasound modulated optical tomography efficient, fast, and motion-artifact free. Expected beam switching time is 10 microseconds. Speed also allows imaging of rapidly varying in time electrically/chemically triggered biological effects. In addition, Doppler effects can be sampled to examine sample temporal behavior. In short, super speed oversampling is possible leading to highly accurate sampled data.

- Beamforming Controls
  The ability to control the power levels and shape/location of each generated optical/ultrasound beam allows smart probing of the biological sample for optimum optical contrast response. As analog tuning is used for optical beam controls, fine tweeking of the wavelength is also possible to optimize sample response.

- No Moving Parts
  As the complete dual-probe uses no moving parts, a compact high reliability sensor can be engineered that has high speed.

- Ultra-Thin Dual Fiber Cable
  Only two strands of typically 250 micron diameter fiber are used to connect the frontend tips to the remoted control optoelectronics. This allows the realization of probe designs for internal optical access applications such as intracavity and endoscopic applications where flexible and small < 2 mm diameter) probes are required.

- Amenable to both In-Coherent and Coherent Designs
  Both low cost incoherent detection and higher sensitivity coherent optical detection can be achieved with the basic proposed probe design. This gives added flexibility to the biomedical user.

Future work relates to the implementation of this dual-probe given available optical and ultrasonic hardware.

REFERENCES

1. D. Dolfi and F. Micheron, “Imaging process and system for transillumination with photon frequency marking,” International patent WO 89/00278 (January 12, 1989).

2. H. W. Tomlinson and J. Tiemann, “Light imaging in a scattering medium, using ultrasonic probing and speckle image differencing,” U.S. patent 5,212,667 (may 18,1993).
3. P.A.Marks, H.W. Tomlinson and G.W. Brooksby, Proc. SPIE 1888, 500 (1993).
4. M. Kempe, M. Larionov, D. Zaslavski, and A. Z. Genack, “Acousto-optic tomography with multiply scattered light,” J. Opt. Soc. Am. A 14, 1151 (1997).
5. L. Wang, S. L. Jacques, and X. Zhao, “Continuos-wave ultrasonic modulation of scattered laser light to image objects in turbid media,” Opt. Lett. 20, 629 (1995).
6. S. Leveque, A. C. Boccara, M. Lebec and H. Saint- Jalmes, “Ultrasonic tagging of photons paths in scattering media: parallel speckle modulation processing,” Opt. Lett. 24, 181 (1999).
7. S. Lev, Z. Kotler and B. G. Sfez, “Ultrasound tagged light imaging in turbid media in a reflectance geometry,” Opt. Lett. 25, 6, (2000).
8. F. Vander Steen, et. al., Ultrasonics, 38, 363-8, 2000.
9. N. Born and J. Roelandt, Intravascular Ultrasound, Dordrecht: Kluwer Academic, 1989.
10. P. Anthony, et.al., “ High frequency ultrasound: Determination of the lowest frequency required for cellular imaging and detection of myocardial disease,” American Heart Journal, Vol. 129, No. 1, pp. 15-19, Jan . 1995.
11. R. S. Adler, et. al., “ Quantitative assessment of cartilage surface roughness in osteoarthritis using high frequency ultrasound,” Ultrasound in Med. And Biol., Vol. 18, No. 1, pp.51-58, 1992.
12. S. Kaul , “Clinical applications of myocardial contrast echo cardiography,” American Journal of Cardiology, Vol. 69, pp. 46H-55H, 1992.
13. N. A. Riza, “Photonically controlled ultrasonic arrays: scenarios and systems,” *IEEE Ultrasonics Symposium*, IEEE Catalog No. 96CH35993, Vol. 2, pp. 1545-1550, Nov. 1996.
14. N. A. Riza and Yu Huang, “High speed optical scanner for multi-dimensional beam pointing and acquisition ,” IEEE LEOS Annual Meeting, Vol. 1, pp. 184-185, 1999.
15. N. A. Riza, Optically Controlled Ultrasonic Probes, Patent No. 5,718,226, Feb.17, 1998.
16. N. A. Riza, Multiplexed Optical Scanner Technology, US Patent Pending.
17. N. A. Riza and M. M. K. Howlader., “Narrowband Ultrasonic Phased Array Control using a Photonic Beamformer,”*Ultrasonics*, Vol.34, No.1, March, pp. 9-18 1996.
18. N. A. Riza, “ High Speed Tunable Bandwidth Ultrasonic Array Beam Steering using Ultra-Compact Photonics,” *Ultrasonics*, Vol. , No. , Jan. , pp. 1998.
19. N. A. Riza, “Wavelength Switched Fiber-Optically Controlled Ultrasonic Intracavity Probes,” *IEEE LEOS Ann. Mtg*. Digest, pp.31-36, Boston, 1996.
20. N. Madamopoulos and N. A. Riza, "Demonstration of an all-digital 7-bit 33-channel photonic delay line for phased-array radars," Applied Optics, Vol. 39, No. 23, pp. 4168 - 4181, 10 August 2000.
21. R. L. Forward, “ Passive Beam Deflecting Apparatus”, US Patent 3612659, 1971
22. N. A. Riza and Y. Huang, “High Speed Optical Scanner for Multi-Dimensional Beam Pointing and Acquisition,” *IEEE-LEOS Annual Meeting*, San Francisco, CA, Nov. 1999.
23. N. A. Riza and Z. Yaqoob, "High speed fiber-optic probe for dynamic blood analysis measurements," European Biomedical Optics Week - EBiOS 2000, SPIE paper 4163-11, Amsterdam, The Netherlands, July 2000.
24. Z. Yaqoob, Azhar A. Rizvi and N. A. Riza, “Free-space wavelength multiplexed optical scanner,” Applied Optics, 40(35), 6425-6438, Dec. 10 (2001).
25. Z. Yaqoob and N. A. Riza, “High-speed scanning probes for internal and external cavity biomedical optics,” OSA Biomedical Topical Meetings, pp. 381-383, Miami, Florida, USA, April 7-10 (2002).
26. Z. Yaqoob, M. Arain, N. A. Riza, “ Wavelength multiplexed optical scanner using photothermorefractive glasses, Applied Optics-IP, Vol. 42, No. 26, p. 5251, Sept. 2003.
27. G. J. Tearney, R. H. Webb, and B. E. Bouma, “Spectrally encoded confocal microscopy,” *Optics Letters*, 23, pp. 1152-1154, August 1, 1998.
28. G. J. Tearney, M. Shishkov, and B. E. Bouma, “Spectrally encoded miniature endoscopy,” *Optics Letters*, 27, pp. 412-414, March 15, 2002.