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# Experiments with Microwave Coherence Tomography: Part 1

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This article presents early work on a microwave version of an imaging technique that has become an important diagnostic tool in its optical application

In the last 10 years, imaging techniques using Optical Coherence Tomography have developed into a new powerful diagnostic tool for ophthalmology. To determine if the technique is practical in the microwave portion of the electromagnetic spectrum, the author has developed a simple experimental setup to test microwave coherence tomography. His experiments suggest that a microwave application is feasible and applications such as industrial sensors may be developed.

In this issue, Part 1 provides background on the technique in its optical version, along with a basic description of the microwave test system. Next month, Part 2 will provide additional detail on the hardware used for the experiments.

## Introduction

The use of Michelson interferometer is well established in optics. Using coherent light sources, interference phenomena are used as a tool to examine source properties as well as to test reflectivity and other properties of various samples.

The concept of partial coherence helped to establish OCT, the Optical Coherence Tomography. Partially coherent light sources in the Michelson interferometer offer to resolve depth features of tested samples. Wavelength "spreading" from a source that is not precisely coherent allows the user to obtain data in one measurement that would require multiple measurements with a coherent source. In optics, the partially coherent source is either a modulation signal on the light beam, or a light source that is narrowband, but not coherent. Practical OCT systems use a "superluminal LED" as a partly-coherent light source.

Figure 1 shows a Michelson interferometer setup adapted for OCT. The interference fringes observed at the photodetector have the following properties:

- Fringe amplitude is proportional to the backscattered light.
- Longitudinal (depth) resolution is $Lc$.
- Coherence length: $Lc = 0.44\lambda^2/\Delta\lambda$, or approx. 2 to 15 µm.

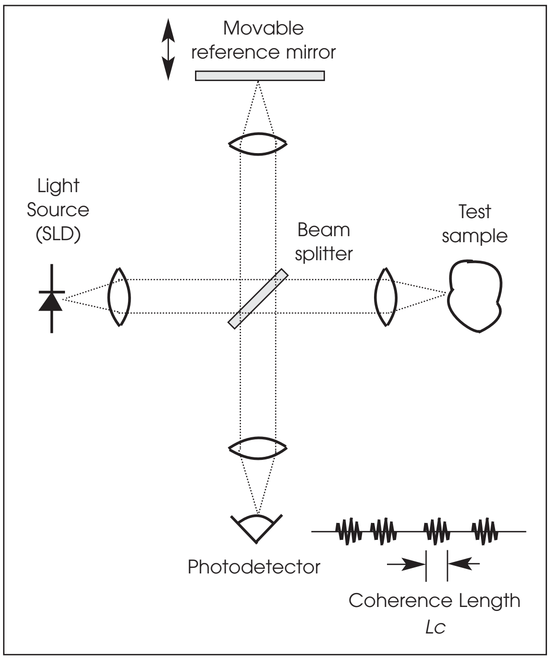


**Figure 1 · Typical features of an OCT system.**

- Lateral resolution by focusing optics is approx. 1 to 10 µm.

To obtain an OCT image, the beam is scanned over the surface of the test sample. Unlike a simple photographic image, the OCT image is three-dimensonal and with signal processing, can provide cross-sectional views of the target area. In ophthalmology, this allows a detailed examination of the retina for study and diagnosis of such problems as macular degeneration or optic nerve damage. Because OCT is a real-time system, these observations can be made *in situ*, allowing the physician or researcher to observe the dynamic conditions.

### Operation at Microwave Frequencies

At microwave wavelengths, typically 3 mm to 3 cm, OCT-type resolution of micrometers cannot be expected (visible light covers wavelengths from ~350 to 650 nm), but cm-range resolution may be useful in applications where visual imaging or radar reflections are not sufficient.

The Michelson interferometer of Figure 1 can be adapted for microwave use as follows:

- Non-coherent microwave noise radiators replace the superluminal

## Background Information on OCT

*The following is a news release from March 2003, issued by the Air Force Office of Scientific Research:*

### Optical Coherence Tomography

*AFRL's Air Force Office of Scientific Research, Physics and Electronics Directorate, Arlington VA*

An Air Force Office of Scientific Research (AFOSR)-sponsored scientist, Dr. James Fujimoto, is the inventor and leading researcher of a new optical imaging tool that could have a profound effect on how medical diagnostics, materials science, and microscopy images are created. Dr. Fujimoto, a professor in the department of Engineering and Computer Science Research Laboratory of Electronics at the Massachusetts Institute of Technology in Cambridge, Massachusetts, and his team of students and collaborators found that optical coherence tomography (OCT) can provide high-resolution, cross-sectional imaging similar to that of ultrasound, only it uses light instead of sound to achieve far greater precision.

OCT, an emerging technology based on fiber optics, often uses a compact diode light source similar to those used in compact disc players. Thus, OCT technology can be robust, portable, low cost, and readily interfaced with optical fiber techniques to catheters, endoscopes, laparoscopes, and surgical probes. These attributes make it very attractive for medical and surgical diagnostics. Other advantages for using OCT in medical diagnostics are to

- Provide images of tissue structure at the micron scale in situ and in real time,
- Function as a type of optical biopsy, unlike the conventional histopathology that requires removal of tissue specimens for microscopic examination,
- Replace standard excisional biopsy when it is hazardous or impossible, possibly reducing sampling errors,
- Enable surgical guidance,
- Enable imaging of organ systems inside the body, and
- Provide image resolutions that are one to two orders above conventional ultrasound.

Healthcare professionals commonly use ultrasound technology to produce diagnostic images. According to Dr. Fujimoto, ultrasound-imaging technology uses sound waves, which travel into the material or tissue and are reflected or backscattered from internal structures with different acoustic properties. The frequency of the sound waves determines the image resolution, with higher frequencies yielding higher resolutions.

Unfortunately, shortfalls exist in ultrasound technology. Primarily, the sound waves lose strength as they travel. Also, there must be physical contact between the instruments and the tissue being examined. Another shortfall is that the depth level of the image is reduced at higher frequencies.

OCT makes up for these shortfalls. In OCT, the echo time delay and intensity of backscattered or back-reflected light is measured from the internal microstructure in materials or tissues. OCT produces images that are two- or three-dimensional data sets, representing differences in optical backscattering.

"Whereas ultrasound pulse propagation and detection can be described in terms of time delays, the echo delay time of light returning to the OCT instrument from the specimen cannot be measured directly by electronic methods due to the high speeds associated with the propagation of light," stated Dr. Stephen Boppart, a former member of Dr. Fujimoto's team, now a professor at the University of Illinois. "Therefore, a technique known as Michelson interferometry is employed, which uses a reference and a sample arm."

With Michelson interferometry, light is split by a fiber coupler with half sent to a reference arm and half sent to the sample arm. One of the fibers directs light to the tissue being imaged and the other fiber to a moving reference mirror. By using a low-coherence-length light source and measuring the interference between light backscattered from the tissue and from the reference mirror, researchers can measure the distance and magnitude of optical scattering within the tissue with micrometer-scale precision (limited by the coherence length of the source).

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LEDs as the signal source.

- A beam splitter can be constructed using dielectric materials.
- The photodetector can be replaced with a sensitive microwave radiometer.
- The mirror can be a simple metallic reflector of proper size and surface precision.
- The mirror can be moved using any of several simple methods.

The hardware for implementation of a MCT system will be desribed in detail in the next part, but here is an overview of the various pieces of the system:

*Noise Source*—Recently, amplified-noise microwave sources have become available but are still expensive. The author has developed simple and efficient noise radiators for this application, using an active

**Background** *continued...*

Scanning a light beam across the tissue produces a cross-sectional image, while a computer records the axial reflectance profiles at each transverse position. The result is a two-dimensional representation of the optical backscattering of the tissue's cross-section, which displays as a gray-scale or false-color image.

Ophthalmology, the study of the eye, is an area of medical research benefitting tremendously from this new technology and the first area to have commercial instrumentation introduced. Dr. Fujimoto stated that studies have been performed to investigate the feasibility of using OCT for the diagnosis and monitoring of retinal diseases such as glaucoma, macular edema, macular hole, central serous chorioretinopathy, age-related macular degeneration, epiretinal membranes, optic disc pits, and choroidal tumors. Since researchers can perform OCT in real time, they are also performing research to measure dynamic responses of the retina to include retinal laser injury.

A particularly hopeful focus of research for OCT includes the diagnosis and monitoring of diseases such as glaucoma and macular edema linked to diabetic retinopathy. Since it can provide quantitative information regarding the disease's progression, Dr. Fujimoto contends that OCT has the potential to detect and diagnose early stages of the disease before physical symptoms and irreversible loss of vision occurs.

Another promising medical area of OCT technology research is in vascular pathology, the study of how fluids, such as blood, travel through the body. Research has shown that most heart attacks result from the rupture of weakened coronary artery walls due to cholesterol-laden plaque, followed by a sequence of biochemical reactions. This rupture could result in thrombosis, vessel occlusion, and possible death. Because these lesions are difficult to detect by conventional radiological techniques, OCT can be useful for intracoronary imaging to identify high-risk atherosclerotic plaques. Although its penetration is limited to a few millimeters, the resolution corresponds to an improvement of over 25 times that of high-frequency ultrasound, magnetic resonance imaging, or computer tomography.

Other AFOSR-funded researchers developed valuable extensions and applications of OCT: Dr. Zhongping Chen, of the University of California, Irvine, developed Doppler OCT in which moving surfaces are observed. This is particularly valuable for studying blood vessel function and fluid flow, generally in small structures. Dr. Johannes de Boer, of the Massachusetts General Hospital (MGH), developed polarization-sensitive OCT and applied it to diagnosing burns and guiding appropriate treatment. Dr. Brett Bouma and Dr. Guillermo Tierney at MGH, both former members of Dr. Fujimoto's group, developed very portable, high-performance OCT systems for clinical diagnostic studies. They have already imaged over 100 patients, and major clinical investigations are ongoing in the fields of gastroenterology, dermatology, cardiology, urology, orthopedics, gynecology, and otolaryngology. OCT is a very promising new optical technology with far-reaching potential.

device combined with an antenna for radiating the microwave signal.

*Beam Splitter*—The beam splitter is a device that is not commonly used for microwaves. Several structures were tested to find a suitable device for the wavelength used in these initial experiements (~2.5 cm). A beam splitter using two parallel dielectric plates was devised and its performance experimentally verified.

*Microwave Radiometer*—In OCT, the light source can have considerable power, but a microwave source may be several orders of magnitude weaker. Thus, a sensitive detector, probably with a multistage amplifier ahead of it, is required. The author adapted a common satellite TV low noise block downconverter (LNB) for this application, including an additional in-line IF amplifier ahead of the detector circuit. The DC output was fed to an X/Y recorder.

*Movable Reference Mirror*—The reference mirror in the interferometer scans a tested sample so that its reflective features may be mapped in depth. A good mirror at microwaves is a flat aluminum plate. To move it as desired, a motorized-screw mechanism from a CD-player was used that offers ~3 cm movement. This movement should be used as X axis on the X/Y recorder, so a 10-turn potentiometer was linked to the mirror to provide an indication of position.

*Tested Samples*—As with OCT, the tested samples should be at least partly translucent to allow penetration of the signal. Reflecting, absorbing and dielectric objects were chosen for the first MCT tests to observe their signatures.

## First Experiments

Figure 2 shows a set of initial test results using various objects on hand. Signatures are well expressed with mirror distances in the range from 9 to 8 cm from the beam splitter. At closer distances, the signatures are weak. This indicates that for a particular interferometer, an optimum range of reference mirror movement must be determined.

Line 7 shows the signature output when no sample was used, so almost no reflection was recorded. On the other hand line 5 shows an intense reflection from an aluminum block in the sample position.

Line 4 also shows a weak signature, this time from a thin-walled polystyrene box. Polystyrene is a low-loss dielectric at microwaves and does not create a significant reflection.

Microwave absorbing materials produced lines 2 and 6, but they were still reflecting enough power for observation. A conductive plastic box produced line 3.

In those experiments, the width of the beam at sample location was not focused by any lens, so no third-dimension resolution was seen. Like in OCT, dielectric lenses will have to be designed and tested to narrow the probing beam at the sample.

The signatures in Figure 2, however, demonstrate the depth resolution, with lines 2 and 5 showing oscillations shorter than 1 cm.

In the next issue, Part 2 will describe the system hardware and experimental results in greater detail.

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