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Advanced Diode Laser Sensors for Industrial Process Control

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The advent of new laser sources has revolutionized the application of lasers in the industrial environment. External cavity diode lasers (ECDL's) and distributed-feedback laser diodes (DFBL's) provide highly controlled, narrowband tunable radiation at a reasonable price, and with good reliability. When combined with modern fiberoptic devices for beam handling and manipulation, this new generation of components allows us to build sensors providing levels of performance that cannot be achieved in any other way. With the new generation of electro-optic devices, these sensor systems can be reliable and affordable, in addition to providing high performance.

Many varied appliations of industrial optical sensing can be successfully served by sensor systems built around these high performance devices. In this paper, we will describe specific industrial sensing applications that we have pursued at Orca, or which are under current development. Typical applications include sensing of metal vapor densithy and velocity for monitoring of vacuum deposition processes, precision monitoring of thin film thicknesses during manufacture, and high sensitivity monitoring of trace gases in indusitrla processing and emissions. A detailed description of the design and performance on one specific industrial laser sensor system will be given as an example.

The electro-optical aspects of sensor system design are just the beginning. Acceptance by industrial users of advanced sensor technology depends not only on sensor performance, but on "real-world" factors such as packaging, reliability, ease of integration, and ease of use. In this paper, we will give a detailed description of some of the steps that we have taken in order to make our sensor systems compatible with the manufacturing environment.

Applications

Most industrial applications for laser sensors can be classified into a few broad application categories:

1. Spectroscopic sensing, most often of gases, within the process environment. The stable, narrowband spectral output of the external cavity diode laser (ECDL) gives excellent specificity These sensors are used to monitor the progression of the process, or to monitor trace species in the final product stream as part of a quality-control protocol.
2. Precision measurement of physical geometry using interferometry. The high coherence available from ECDL's and DFBL's provides excellent performance in interferometric sensors.
3. Metrology using a variety of edge-location and imaging techniques.These measurements do not generally require narrowband laser sources, and are byond the scope of this paper.

Case Study: Metal Vapor Deposition Measurement

Vacuum evaporation and deposition of metals is used in a wide variety of high-value manufacturing processes. Examples include semiconductor device manufacture, manufacture of composite materials, and production of high-purity metal feed stocks.

As an example of one specific application, we will describe a sensor system that was developed for monitoring of deposition of Barium and Yttrium during the manufacture of high-temperature superconducting devices. The manufacturing process consists of simultaneous vacuum deposition of three metals: Barium, Yttrium and Copper, in a vacuum environment with a controlled Oxygen background. The desired result is deposition of a thin film with all 3 metals in a very uniform mix.

The accuracy and uniformity of the metal mixture in the final film is one factor that directly affects the superconducting transition temperature and RF losses of the product. In order to optimize superconductor performance, it is necessary to simultaneously measure, and to control, the deposition of *each* individual metal component.. For this purpose, we have developed, delivered, and tested sensor systems for Barium and Yttrium. A system for measurement of Cu is still under development.

In the rest of this paper, we will give a detailed description of the sensor system for measurement of Barium deposition rate. Figure 1 shows a simplified schematic of the measurement geometry. All of the components of the sensor system are housed in a package that can be located remotely from the processing facility. Light from the laser source is taken to the process chamber by a fiber optic system, interacts with the metal vapor inside the process, and then is returned to the sensor via fiber optics for detectiona and signal processing.. In this case, the senor measures the absorption due to a single near-infrared absorption line of the Barium atom.

In actual practice, the measurement geometry is slightly more complex than shown in Figure 1. Figure 2 shows more detail. Instead of just crossing the evaporation beam in a single pass, a double-pass geometry is used. A thermally-shielded retroflector assembly is mounted inside the vacuum chamber. This increases the sensitivity of themmeasurement by increasing the effective absorption path length. It also means that only one optical window is required on the deposition vacuum system.

In addition, the optical beam is tilted at about 5° withrespect to the transverse direction of the atomic velocity. In this geometry, the optical sen-

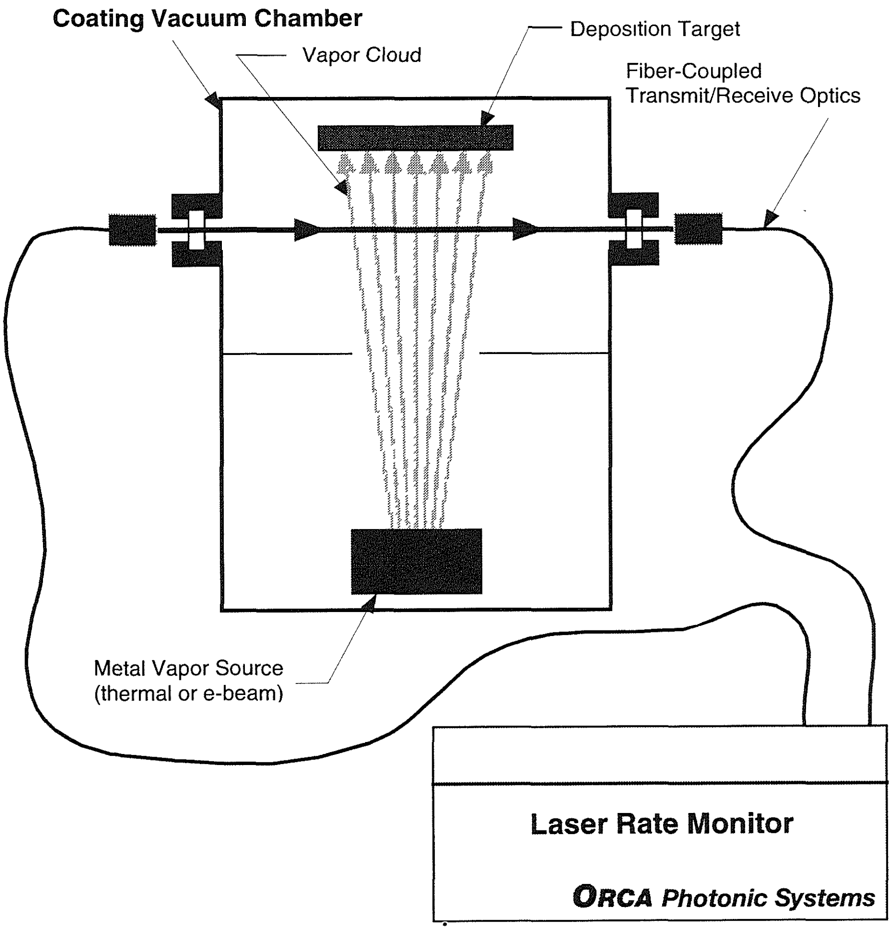

Figure 1. Schematic of geometry for a typical process sensing application.

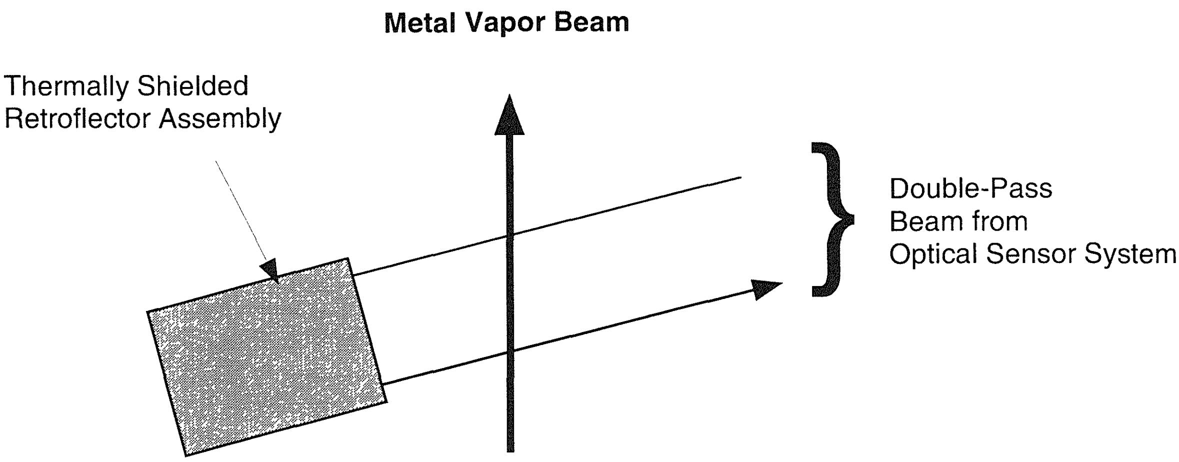

Figure 2. Double-pass optical geometry used for metal vapor sensing. The optical beam crosses the metal-vapor beam twice, and is tilted at a slight angle (~5°) with respect to the atomic beam axis (see text).

sor becomes sensitive to the atomic *velocity*, as well as the atomic density. On the incoming pass the optical beam is looking "into" the atomic beam, and the center of the absorption line is shifted upward in frequency. On the outgoing pass, the optical beam is going "away" from the atomic velocity, and the absorption line is shifted downward. As a result, the absorption feature as measured by sensor is split into two distinct Doppler components. The magnitude of the frequency splitting is a direct indication of atomic velocity. The magnitude of the absorption directly relates to atomic density. As a result, we can extract a measurement of atomic *flux* (i.e. density x velcoity) from the optical sensor, with no additional external information.

Figure 3 shows an example of a Barium absorption spectrum that we typically measure. This spectrum was acquired under actual conditions typical of high temperature superconductor manufacture. Spectrum acquisition is done using a frequency-modulation technique with synchronous detection, in order to maximize sensitivity. We have demonstrated that we can measure absorptions down to the order of 10^{-5} with 1 msec per point acquisition times. The spectrum shown in Figure 3 was acquired in 250 milliseconds. The sensor continues to acquire spectra continuously at this rate.

Because of the very high data acquisition rate (which can be programmed values in the range of 1 to >10 Hz), the sensor system can support closed-loop control of the deposition rate, which is accomplished by controlling the electron-beam source which drives the evaporation. We ahve successfully demonstrated closed-loop e-beam control with a bandwidth of aproximately 3 Hz, and residual rate errors of order 1%.

Figure 4 shows a photograph of the complete Barium sensor system. The entire system is mounted in 3 rackmount boxes, which house the optical system, the laser controller, and the system computer (from top to bottom).

Data Delivery

Another important concern to industrial users is ease of integration with the computerized control systems that are now part of nearly every manufacturing facility. We have developed unique, highly flexible methods of delivering data using TCP/IP networking and industry-stanmdard Internet protocols. To the network, the entire sensor system is a "data server" that simply delivers either absorption spectra, or integrated density and flux values, on request..

Acknowledgements

The metal vapor sensor system was developed in collaboration with Dr. Evan Green, of Focused Research, Inc. Testing of the sensor system on a vacuum deposition system with superconducting materials was completed in cooperation with Dr. Vladimir Matijasevic, of Conductus corporation.

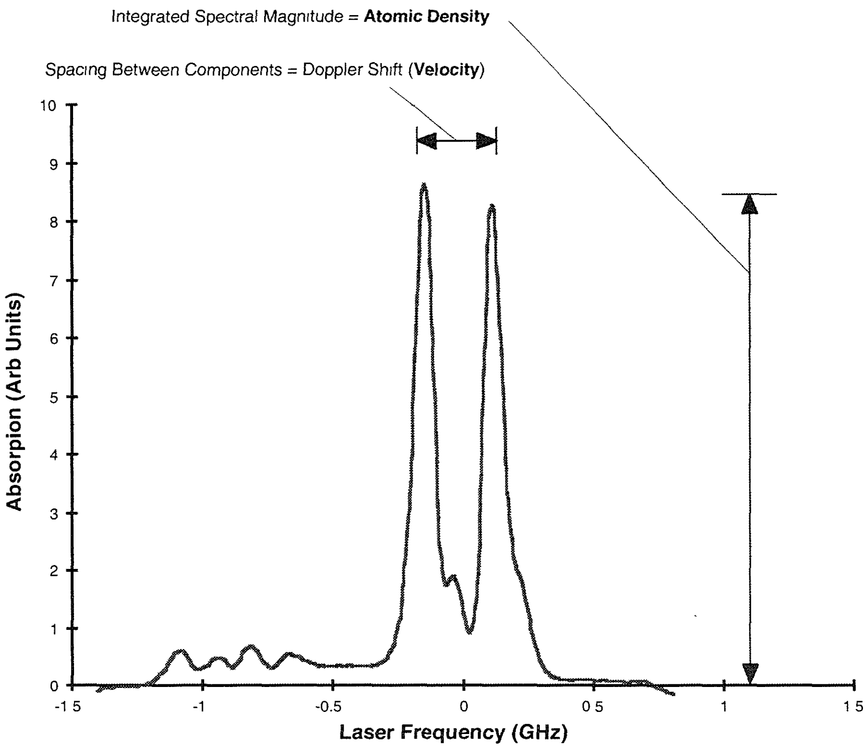

Figure 3. Typical Barium absorption spectrum acquired under production conditions.The acquisition time for this entire spectrum was 250 milliseconds. Peak absorption is of order 100 ppm.

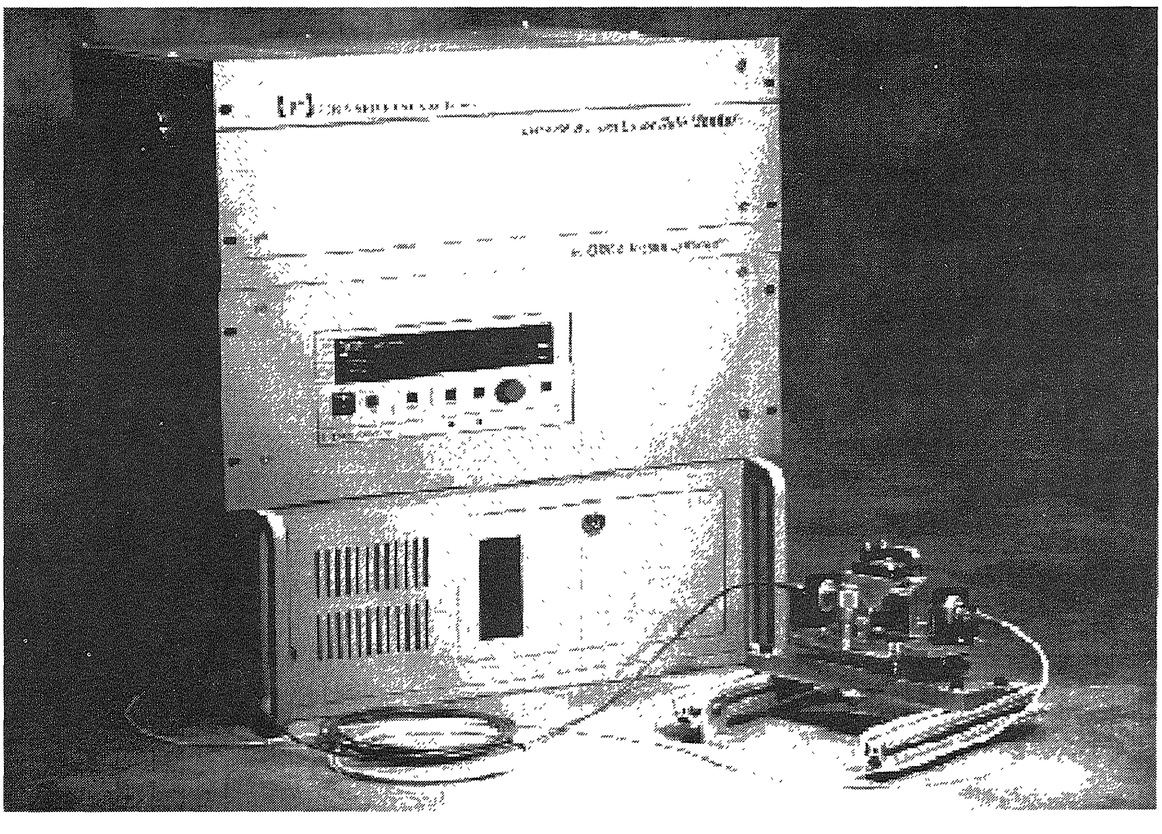

Figure 4. Photograph of the complete Barium sensor system, including data processing. The chamber interface optics are shown at the lower right.