Lasers for Nanometrology

Low noise fiber-coupled laser diode beam sources with reduced coherence

Over the last few decades the interest in phenomena on nanoscale or even atomic scale has increased significantly. A prominent, but at the same time very demanding technique is atomic force microscopy (AFM). AFM can reveal surface topographies at atomic resolution or be used to measure small forces in the range of only a few piconewtons. This exacting technique requires highly stable laser sources with specific features, including low power noise and the possibility to suppress unwanted interference.

The 51nano series of lasers was specially developed to provide these indispensable features of low noise, reduced coherence and low speckle contrast in order to achieve the demanding stability standards required in nanotechnology and atomic force measurements. Particle measurements and alignment tasks are other possible applications for these stabilized, fiber-coupled laser diode beam sources.

Conventional singlemode laser diodes are semiconductor lasers and usually have one favored longitudinal mode. However, the semiconductor laser material exhibits a temperature dependency, altering the gain profile and refractive index, so that a different longitudinal mode is excited stochastically. This mode hopping causes the output wavelength to jump rapidly by a few pm [1]. For non-stabilized singlemode diodes the output power can change erratically by as much as 3%. These disturbances are intensified when laser light is back-reflected into the laser diode, either through direct reflection or simply through back-scattering.

Back-reflection can be prevented effectively by coupling the laser beam source using an optical fiber in which the fiber endface has been polished at an oblique angle. Since some form of back-coupling into the laser diode, e.g., due to back-scattering in the fiber itself, however, cannot be avoided completely, fiber-coupled laser diode beam sources often exhibit an increased power noise.

The undesirable features of power noise and mode hopping are eliminated in the 51nano series by modulating the current of the laser diodes at a frequency around 0.5 GHz. This RF-modulation excites numerous longitudinal modes of emission while simultaneously lowering signal noise significantly to <0.1 % RMS. This induced broadening of the spectrum, in a controlled and stable way, has the added advantage of considerably reducing the coherence length of the laser beam which, in turn, reduces laser speckle contrast and suppresses the generation of interference patterns. For measurement tasks, where back-coupled light is inherent to the method, a Faraday isolator...
(series 51nanoFl), serving as an optical diode, protects the laser diode, guaranteeing a stable mode of operation (Figure 1).

**Comparison with standard laser diode beam sources**

The notable benefits of RF-modulated laser diode beam sources become visible when comparing them with the features of a standard fiber-coupled laser diode beam source. Figure 3 depicts noise, spectrum, laser speckle as well as interference behavior when using a laser of type 51nano, Figure 2 when using a standard laser diode beam source.

In order to improve comparability, the same 51nano is used as a standard source only with RF-modulation switched-off. In this configuration a 51nano does not differ much from any other standard fiber-coupled laser diode beam source.

In Figure 2A and 3A two noise measurements (bandwidth of 1MHz, period of 60 minutes) are contrasted with each other. Peak values in noise exceed 1 % for a standard laser diode while the RF-modulation of the 51nano reduces noise to <0.1 %, a value close to the detection limit.

**Temperature behavior**

Every semiconductor-based laser without an external mechanism of stabilization exhibits a drift of the emitted center wavelength with changing temperature. The temperature dependence is intrinsic to the semiconductor material and so the refractive index and gain profile are altered. For GaAs-based diodes, a drift of 2.3 to 3 nm is produced by a temperature increase of 10°C, e.g., from 20–30°C.

The effect of temperature on the desired center wavelength can also be observed for lasers of type 51nano. Although the RF-modulation leads to a broader spectrum, the center wavelength still varies with temperature and the whole „comb“ drifts slightly. The incorporation of an integrated temperature control, in the 51nanoTE, effectively stabilizes the center wavelength to the desired value. A positive side effect of additionally reducing the temperature is that the lifetime of the laser diode is increased significantly.

**Atomic Force Microscopy**

A major field of application of the laser diode beam source 51nano is atomic force microscopy (AFM).
This measurement method is based on scanning the surface of a sample with the tip of a cantilever, which is brought close to the sample surface. A piezo-element moves the tip relatively to the sample. Atomic forces (such as Van der Waals or electrostatic forces) between the tip and the sample cause a deflection of the cantilever. By evaluating this interaction, conclusions can be drawn about the surface structure, surface composition and the physical properties.

The resolution of an AFM is mainly dependent on the curvature of the cantilever tip. Lateral resolution reaches beyond the limits of diffraction down to only a few Ångström (10^{-10} m) and allows single atoms in nanostructures, such as carbon nanotubes or graphene, to be visualized.

AFM can also be used to measure small forces directly with high precision. In a slightly adapted setup, the force exerted by a single muscle fiber of only a few piconewtons can be resolved [3].

Besides measuring and imaging, AFM is also utilized to manipulate matter on a nanometer scale and has been employed to remove single atoms from a surface, to deposit and position atoms or to nano-structure the surface.

Most AFMs are based on two different working principles: laser deflection measurement or fiber-optic Fabry-Perot interferometry.

**Laser Deflection Measurement**

In order to measure the deflection of the cantilever, a laser spot is placed on the back of the cantilever tip under a certain angle. Its reflection is then detected by a position sensitive diode. The position of this spot has to be detected very precisely, since it is the basis for the evaluation of the AFM measurement. Interference (e.g., from reflections at

![FIGURE 4: System components for comparative measurements between a stabilized and a standard laser diode beam source. Light exiting the 51nanoFI (A) is guided through the fiber-optic beam splitter (50/50) (B) onto a mirror (D), which is oscillated by a piezo-element (E). The light emanating from the fiber is partially back-reflected at the fiber end-face (C) and is also reflected by the moving mirror. The interference signal is recorded by a photodiode with transimpedance converter (G) and the spectrum of the laser source with a spectrometer (F).](image)

**INFOBOX**

**Evaluation of the 51nanoFI during simulation of Atomic Force Microscopy**

A feasibility study of the use of the laser diode beam source 51nanoFI in atomic force microscopy (AFM) was successfully performed as a simulation in cooperation with Prof. Dr. H.-J. Eifert, MND, FH Gießen-Friedberg [2].

A 51nanoFI beam source that can be switched between two different states, non-stabilized (without RF-modulation) or stabilized (with RF-modulation) was used as a fiber-coupled laser source (see Fig. 4). The radiation was split using a 50/50 fiber-optical beam splitter. One portion is directed to a spectrometer to analyze the spectral power density of the source. The other part is guided to a mirror under piezo-control that oscillates sinusoidally with a frequency of 1.5 kHz. Fresnel reflection causes a small part of the radiation to be reflected at the fiber end-face, which interferes with the light that is reflected by the oscillating mirror (fiber-optic Fabry-Perot Interferometer).

The interference signal is then split again at the fiber-optical beam splitter. The part of the signal coming back to the laser source is suppressed by an integrated Faraday isolator that serves as an optical diode, while the other part is detected by a photodiode. A specifically developed transimpedance converter (threshold frequency 6 MHz) then transforms the photodiode signal into an oscilloscopic voltage signal. For mirror movements within the frequency range 100 Hz to 1.5 kHz, the stabilized beam produced by the 51nanoFI laser diode exhibits a highly stable interferometer signal with low noise (Fig. 5A).

Without RF-modulation, mode hopping and undesirable interference result in signal noise that varies stochastically (screenshots 5B and 5C). Productive interferometer measurements (induced by mirror oscillations to represent the cantilever movements in AFM) are only feasible when using a 51nanoFI, a stabilized laser diode together with an integrated Faraday isolator.

![FIGURE 5: Interferometric signal using a 51nanoFI (A) compared with the unstable interferometric signal using the laser source without RF-modulation (B, C).](image)
the protective window of the detector) or laser speckle on the detector constrain the resolution of this signal. Using the RF-modulated beam source 51nano, the interference at surfaces with optical path differences longer than the coherence length of the source (here 300 μm) is suppressed and the speckle contrast is reduced, thus enhancing signal quality.

Fabry-Perot interferometry
The optical scheme for detecting cantilever deflection using interferometry is depicted in Figure 6. The laser light emitted by the laser source is guided through a fiber-optical beam splitter and then onto the cantilever tip. The light emanating from the fiber is partially back-reflected at the fiber end-face (approx. 4%) and is also reflected by the oscillating cantilever. These two waves interfere and the interference signal is passed through the beam splitter to the detector. The signal reaching back to the laser source is blocked using an integrated Faraday isolator.

The phase difference between the interfering waves serves as a measure of the cantilever deflection. Unfortunately, the desired interference signal between the fiber end-face and cantilever is disturbed by interference from reflections at all fiber ends and between the detector and the fiber end-face.

The noise in the signal can be suppressed by using the RF-modulated 51nanoFI laser source. The small coherence length ensures that only the desired interference signal, between the fiber end-face and the cantilever, actually contributes to the signal and the signal quality is enhanced.

A convincing demonstration of how RF-modulation improves signal quality in AFM-measurements was performed in a thesis using the 51nanoFI laser source [2], see box. The AFM signal of the cantilever deflection was simulated using an oscillating mirror (see Figures 4 and 5) and a stable interferometric signal was only achieved when using the RF-modulated 51nanoFI.

The fiber-optic system has the added advantage that only the fiber itself needs to be placed in direct proximity to the sample, not the detection of the signal. This is particularly useful when the experiments are conducted in a vacuum chamber.

Back-Reflection Particle Measurement
The 51nano series can also be used for particle measurement by back-reflection. The radiation of the laser source is guided via a singlemode fiber and a fiber-optical beam splitter onto the particle flow (Figure 7).

Particles passing through the focused beam cause the light to scatter and some is back-reflected into the fiber. Precise measurements require low speckle contrast and a constant laser power without noise. By using a 51nano, the coherence length is reduced, and the power averaged, resulting in a detected signal with much less noise.

The laserseries 51nano is available in a wavelength range from 405–1550 nm. For the collimation of the beam, Schäfter+Kirchhoff offers a large variety of different fiber collimators, micro-focus optics and filters. Also available are, e.g., vacuum feed-throughs and fiber-optical beam splitters.

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