

# Lasers for Atomic Force Microscopy

Low noise fiber-coupled laser sources with reduced coherence

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Over the last few decades, the interest in phenomena on nanoscale or even atomic scale has increased significantly. A prominent, but 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 a few piconewtons. This technique requires highly stable laser sources with very specific features. The 51nano series of lasers was specially developed to provide low noise, reduced coherence, and low speckle contrast in order to achieve the stability standards required in nanotechnology and atomic force measurements. Particle measurements and alignment tasks are other possible applications for these laser 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 other longitudinal modes are amplified stochastically. This mode hopping causes the output wavelength to jump rapidly by a few nanometres [1]. For non-stabilized singlemode diodes the output power can change erratically by as much as 3 percent. 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 end-face has been polished at an oblique angle. However, since some form of back-coupling into the laser diode, e.g.,

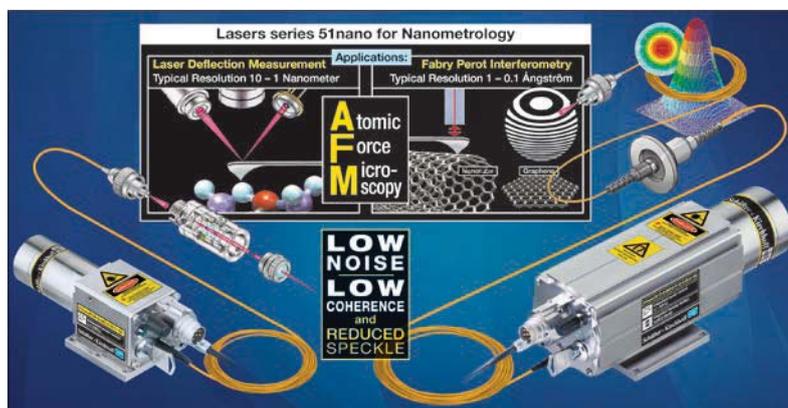


Fig. 1 Laser beam sources of the 51nano series. The radiation is guided through a vacuum-feedthrough to the experiment with the help of a fiber collimator with

micro-focus. Both FC-PC connector and collimator are optionally made from amagnetic titan.

due to back-scattering in the fiber 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 high frequency. This RF-modulation excites numerous longitudinal modes of emission while simultaneously lowering signal noise significantly to < 0.1 percent RMS. This induced broadening of the spectrum, in a controlled and stable way, has the 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 51nanoFI), serving as an optical diode, protects the laser diode, guaranteeing a stable mode of operation.

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. Fig. 3 depicts noise, spectrum and laser speckle as well as interference behavior when using a laser of type 51nano, Fig. 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 Fig. 2a and 3a two noise measurements (threshold of 1 MHz, period of 60 minutes) are compared to each other. Peak values in noise exceed more than one percent for a standard laser diode while the RF-modulation of the 51nano reduces noise to less than 0.1 percent, a value close to the detection limit.

Without RF-modulation, the laser jumps stochastically between several emitting modes (Fig. 2b, different colors). Upon RF-modulation, numerous modes are excited within the gain profile of the resonator (Fig. 3b), producing a broad spectrum with about 1.5 nm full width at half maximum (FWHM).

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Fig. 2c and 3c show the corresponding laser speckle behavior, a frequent problem in optical metrology. Speckle arises from multiple interference, e.g., diffuse reflection of laser radiation on optically rough surfaces ( $> \lambda/4$ ). For fully coherent laser sources, the laser speckle contrast is 1 with areas of zero intensity within a laser spot. Due to the emission from multiple laser modes the coherence length of type 51nano lasers is reduced to less than 300  $\mu\text{m}$  and the speckle contrast is lowered (compare Fig. 2c with Fig. 3c).

Another effect of a reduced coherence length can be observed in Fig. 2d and 3d. The recording of a collimated laser beam by a CCD area scan camera reveals a disturbing interference pattern when using a standard laser diode (Fig. 2d) caused by internal reflection within the protective glass window of the detector. The coherence length of the 51nano is reduced to a value less than the thickness of the glass, and no interference arises (Fig. 3d).

## 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 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  $^{\circ}\text{C}$ , e.g., from 20 to 30  $^{\circ}\text{C}$ .

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 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 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 either moves the tip over the sample or the sample is moved under the tip. 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 ( $10^{-12}$  N) can be resolved [2].

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

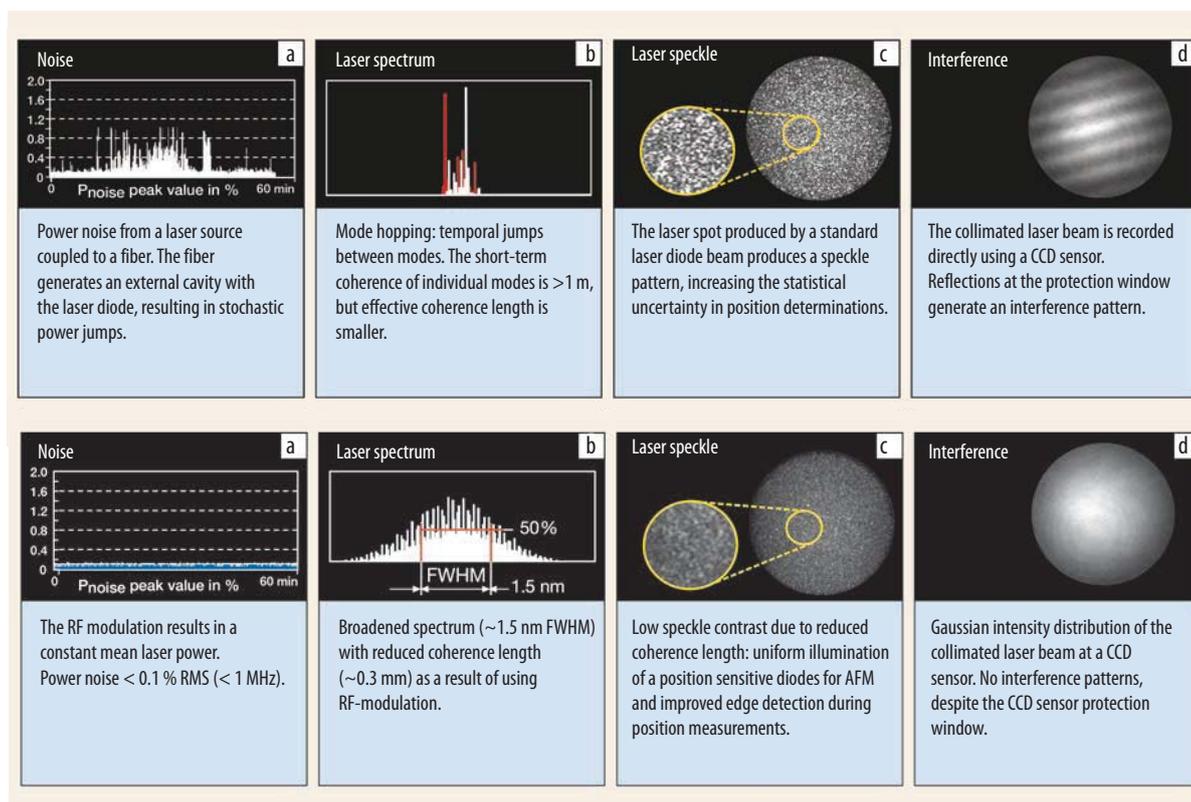


Fig. 2 Characteristics of a standard fiber-coupled laser diode beam source. High noise, mode hopping, laser speckle, and unwanted interference can constrain the optical resolution.

Fig. 3 Advantages of the laser diode beam source 51nano with lower noise (a), spectral broadening (b), reduced laser speckle (c), and less interference (d).

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. With a laser deflection measurement typical resolutions of 10 to 1 nm are reached, with Fabry-Perot interferometry, the limit is about ten times lower, i.e., down to about 1 Å. A fiber-optic system has the 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.

## 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 the protective window of the detector) or laser speckle on the detector constrain the resolution of this signal. Using a RF-modulated beam source, 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 Fig. 6. The laser light emitted by the diode 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 (approximately four percent) and is also reflected by the oscillating cantilever. These two waves interfere, and the interference signal is passed

## 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 Hans-Justus Eifert, MND, FH Gießen-Friedberg [3].

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 (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 in-

terferes 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 photo 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 (Fig. 5b, c). Productive interferometer measurements (induced by mirror oscillations to represent the cantilever movements in AFM) are only feasible when using a stabilized laser diode together with an integrated Faraday isolator.



Fig. 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 the 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).

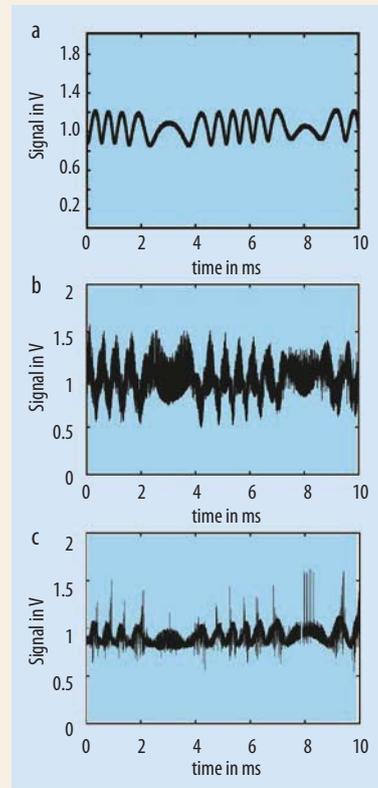
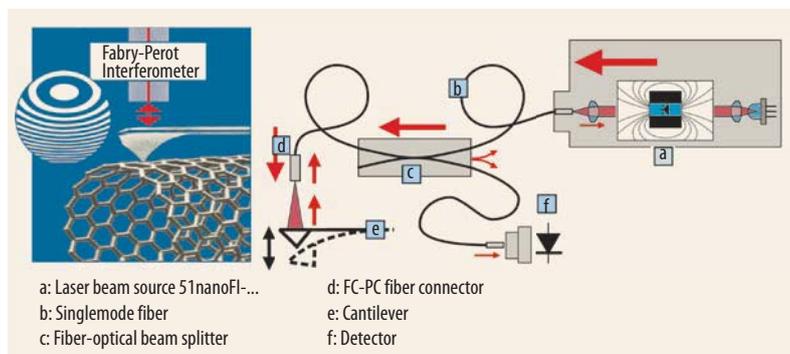


Fig. 5 Interferometric signal using a 51nano (a) compared to the unstable interferometric signal using the laser source without RF-modulation (b, c).



**Fig. 6** The optical scheme of a fiber-optic Fabry-Perot Interferometer in an Atomic Force Microscope. Laser light is passed through a fiber-optical beam splitter and reaches the cantilever. The

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 confused 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

interference between the reflection at the fiber end-face and the moving cantilever is recorded by the detector. Signal quality is improved by using a 51nanoFI.

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 research assignment using the 51nanoFI laser source (**infobox**) [3]. The AFM signal of the cantilever deflection was simulated using an oscillating mirror (**Fig. 4 and 5**) and a stable interferometric signal was only achieved when using the RF-modulated 51nanoFI.

### Back-Reflection Measurement

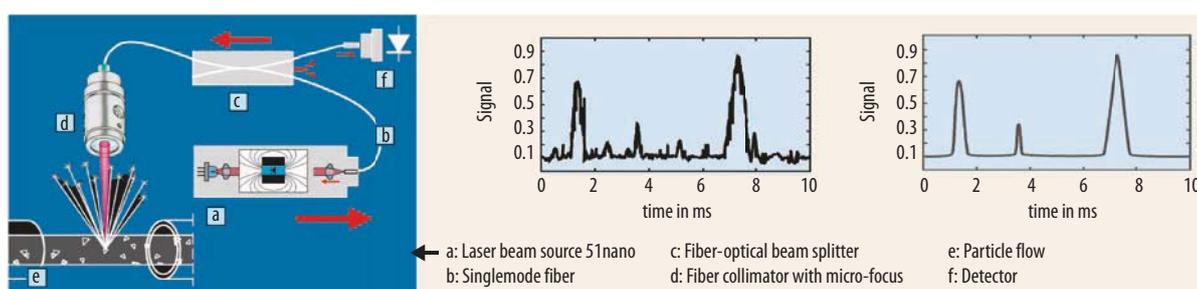
The 51nano series can also be used for particle measurements by back-

reflection. The radiation of the laser source is guided via a singlemode fiber and a fiber-optical beam splitter onto the particle flow (**Fig. 7**).

Particles passing through the focused beam cause the light to scatter, and some light is back-reflected into the emitting 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 laser series 51nano is available in a wavelength range from 375 to 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.

- [1] K. Petermann, *Laser Diode Modulation and Noise*, Kluwer, Dordrecht (1991)
- [2] [www.mh-hannover.de/1102.html](http://www.mh-hannover.de/1102.html)
- [3] M. Schulz, *Aufbau eines Messsystems zur Evaluierung einer Laser Beam Source für die Rasterkraftmikroskopie*, Diplomarbeit, Fachbereich Mathematik, Naturwissenschaften und Datenverarbeitung, FH Gießen-Friedberg (2009)



**Fig. 7** Optical scheme for back-reflection particle measurement. Particles scatter light back into the fiber. The precision of the measurement is enhanced by using a beam source with low power noise.