Optica Applicata, Vol. XLI, No. 2, 2011

Radio frequency modulation of semiconductor laser as an improvement method of noise performance of scanning probe microscopy position sensitive detectors

Jan M. SKWIERCZYŃSKI, Grzegorz MAŁOZIĘĆ, Daniel KOPIEC, Konrad NIERADKA, Jacek RADOJEWSKI, Teodor P. GOTSZALK

Wrocław University of Technology, Faculty of Microsystem Electronics and Photonics, Janiszewskiego 11/17, 50-372 Wrocław, Poland

An experimental investigation was made on use of radio frequency (RF) modulation of a semiconductor laser in order to improve the noise performance of the scanning probe microscopy cantilever position sensitive detector. High resolution measurements of the cantilever displacement are limited by optical power intensity noise of the laser diode. In general, the intensity noise is formed by mode hopping or mode partition phenomena in the laser multimode and single mode regimes. Furthermore, the measurements are disturbed by an optical feedback, which is caused when light is scattered back into the laser cavity. In order to reduce the laser intensity noise and the optical feedback, we developed a precise laser automatic power control (APC) driver with RF modulation of the DC diode bias current. Our experiments showed that the spectral noise density of the developed scanning probe microscopy detection system was 3 times smaller than the noise density of the system without RF operating current modulation. In a low power operation, near the diode threshold current, the laser mode partition noise is dominating and it can be reduced by adjusting the modulation current frequency to 300 MHz. In this paper, the architecture of the designed system will be presented. We will also discuss the results of noise performance investigations of the scanning probe microscopy position sensitive detectors applied in precise surface measurements.

Keywords: intensity noise, mode hopping, mode partition, semiconductor laser, RF modulation.

1. Introduction

Scanning probe microscopes (SPMs) can be applied in versatile high-resolution surface investigations. By line surface scanning and data acquisition of signals corresponding with cantilever deflection, the sample properties are analyzed in the form of three-dimensional images [1]. The most popular system to detect the SPM cantilever deflection is the position sensitive detection (PSD) method. In this method, a semiconductor laser, whose optical power is stabilized, is used to illuminate the SPM spring beam. The light, which is reflected from the sensor, is analyzed with a segmented photodetector. In this way not only the deflection signal but also intensity noise of the semiconductor laser are amplified, which limits the resolution of the SPM. Therefore, an improvement in the noise performance of the light source used in the microscope becomes a key issue. Optical power fluctuations of the semiconductor laser are caused by mode hopping in single mode regimes (the bistable regime in which the oscillating mode is changing between two longitudinal modes) or partition mode phenomena of the semiconductor laser in multimode regimes [2, 3].

The RF modulation of the DC diode bias current enables reduction of the laser intensity noise. The high frequency oscillation of the semiconductor laser DC current forces the laser to operate in the multimode mode, in which, however, the DC power is still maintained [4]. In addition, the AC modulation of the current flowing through the laser at the frequency of 100–600 MHz reduces the coherence of the laser beam. This results in controllable and stable modulation of the laser radiation, which is synchronized with the RF generator. Furthermore, the laser becomes less sensitive to the optical feedback and the spontaneous emission noise [5]. In this way, the high resolution investigations in liquid environment, in which light reflections can be observed, are enabled [6].

2. Low noise automatic power control (APC) system

A monitor photodiode (MPD) integrated in the laser casing is used to monitor the laser diode (LD) radiation. The automatic power control (APC) system maintains the optical power of the semi-conductor laser. In this set-up, the current of the MPD reflects the radiation of the LD. The bias current flowing through the laser is controlled, so that the signal from the MPD remains at the defined level. The above relationship illustrates the diagram in Fig. 1, which was recorded for the diode Sanyo DL-3147-060. The entire system is controlled with an ATmega microprocessor, which is responsible for the setpoint and control limits definions. The current regulation is realized with a precision current source ADN2830, which is controlled by two-channel digital

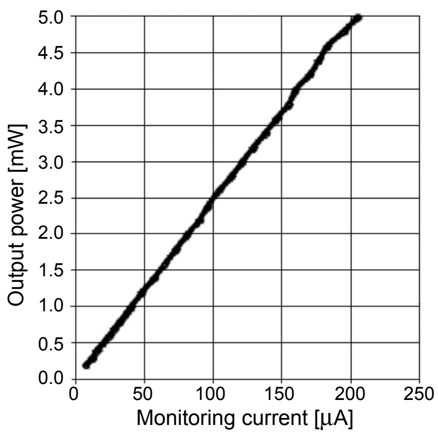


Fig. 1. Optical power of the Sanyo DL-3147-060 semiconductor laser versus MPD current.

potentiometers ADN2850. In this way, high reliability, signal-to-noise ratio and flexibility of the designed system are ensured.

Laser diodes have a built-in photodiode (MPD). APC system determines the exact optical power of a semiconductor laser due to the current generated by the photodiode, which is directly proportional to the radiation and accurately reflects the value of the optical power emitted by the laser. The above relationship is shown in Fig. 1. In order to reduce a noise inside the power supply, a battery was mounted, which allows us to work five days long without any external power supply. With an intuitive user interface, it is possible to set easily the laser optical power and the current limits. In APC system, the ATmega32 processor programmed in C language is running. The current regulation is made with the precision current source ADN2830, which is controlled by a two-channel digital potentiometer ADN2850. The advantages of APC system are reliability, mobility and a low-noise operation.

3. RF modulation system

In our system we use a EL6204 current source for the RF modulation of the LD. An internal clock switches the current sources, which act as a powerful push–pull oscillator. The operation principle of the EL6204 integrated circuit is shown in Fig. 2. The frequency and the amplitude of the modulation current are set independently by R_{FREQ} and R_{AMP} resistors.

The RF modulation frequency is calculated as a function of R_{FREQ} resistance using the following equation:

$$\text{Frequency [MHz]} = \frac{1824}{R_{\mathrm{FREQ}}\ [\mathrm{k\Omega}]} - 2.2$$

In Table 1 we summarized resistances of R_{FREQ} and R_{AMP} resistors for the modulation frequencies changing in the frequency range from 50 MHz up to 500 MHz.

The designed and fabricated system consists of three circuit boards (PCBs) which are connected vertically – Fig. 3. This architecture ensures miniaturization of the cur-

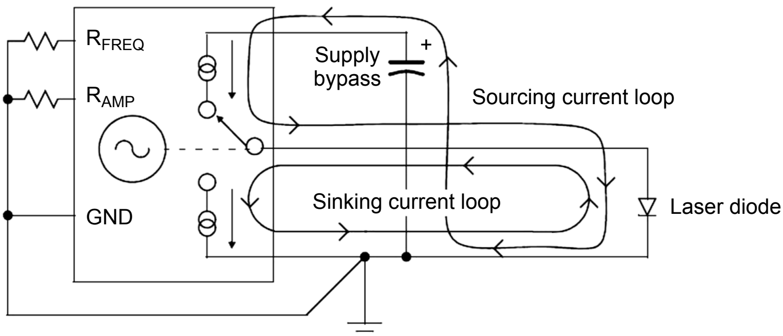
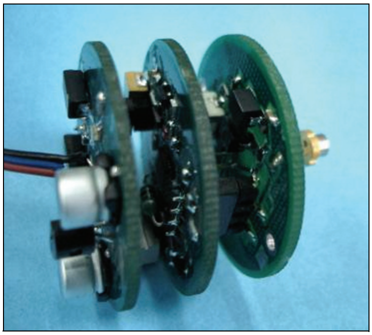


Fig. 2. The operation principle of EL6204.

Table 1. Resistance of R_{FREQ} and R_{AMP} resistors for various frequencies and amplitudes of the LD modulation current.

Frequency [MHz]	R_{FREQ} [kΩ]	I_{AMP} [mA]	R_{AMP} [kΩ]
50	34.28	10	10.5
100	16.04	15	6.27
150	9.96	20	4.15
200	6.92	25	2.88
250	5.1	30	2.03
300	3.88	35	1.43
350	3.01	40	0.98
400	2.36	45	0.62
450	1.85	50	0.34
500	1.45	55	0.11


a

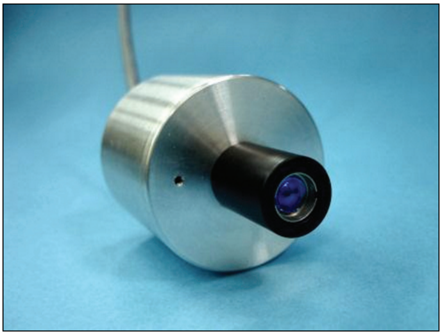

b

Fig. 3. RF modulator of the laser DC bias current: measurement and control electronics (**a**), packaged device with laser collimator (**b**).

rent modulator and enables integration with the SPM measurement head. The lateral and vertical dimensions of the designed device do not exceed 4 cm. Furthermore, by reducing the distance between the optical power controller and the RF oscillator, the wiring inductances are reduced, which ensures proper RF biasing of the LD.

The first circuit board integrates the EL6204 current source and is directly connected with the LD. The miniaturized APC laser driver with the ADN2830 controller is mounted on the second board. The third board contains a voltage regulator LM7805, which ensures a low noise 5 V power supply.

4. Optical power intensity noise measurements

The noise measurements of the LD were performed using a precise and wide bandwidth measurement electronics. It consisted of a low capacitance photodetector and low noise preamplifier. On the top of the battery supplied device the SPM collimator unit with the RF modulated LD was placed – Fig. 4. In Figure 5 we show

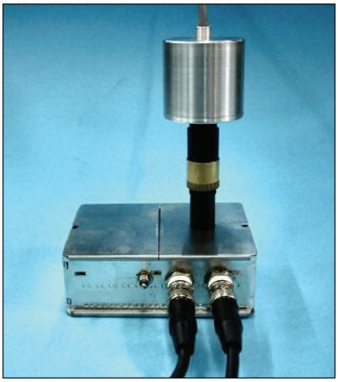


Fig. 4. Measurement electronics for noise characterization of the LD.

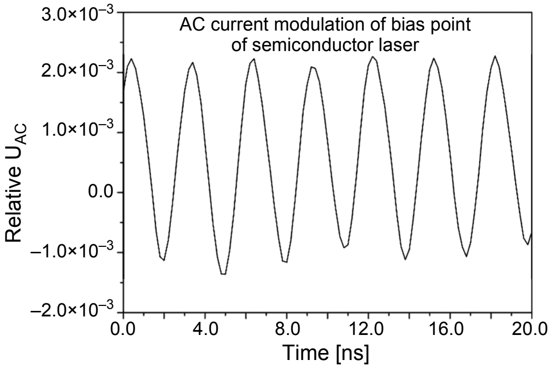


Fig. 5. RF modulation of the LD laser current at frequency of 310 MHz.

the RF signal corresponding with the LD modulation at the frequency of 310 MHz (R_{FREQ} = 3.68 kΩ), which was detected using the developed measurement electronics.

The noise performance of the Sanyo DL-3147-060 LD was observed for various levels of the DC laser power, when the DC diode bias current was switched on and off. In Table 2 we summarize radiation power, DC bias current and modulation frequency, at which the noise properties of the tested LD were recorded. Next, we calculated the root-mean-square (RMS) and Pk–Pk values of the measured noise signals. In Table 3 the intensity noise parameters for different optical powers were compared. For the DC power of 2 mW, at which the mode hopping is a dominant noise source, we recorded three times smaller intensity noise, when the DC bias current modulation was on.

T a b l e 2. Radiation power, DC bias current and modulation frequency of the tested LD.

Power [mW]	Frequency [MHz]	I_{AMP} [mA]
3.5	300	18–34
3.0	300	10–18
2.5	280	9.5
1.0	185	9–20
0.2	200	11–15.5

T a b l e 3. Comparison of the intensity noise parameters for different optical powers.

Power [mW]	RMS_{AVG} comparison	$V_{AVG\ Pk-Pk}$ comparison
3.5	5.4	2.7
3.0	3.2	2.6
2.5	3.1	2.4
1.0	3.3	2.5
0.2	1.8	1.7

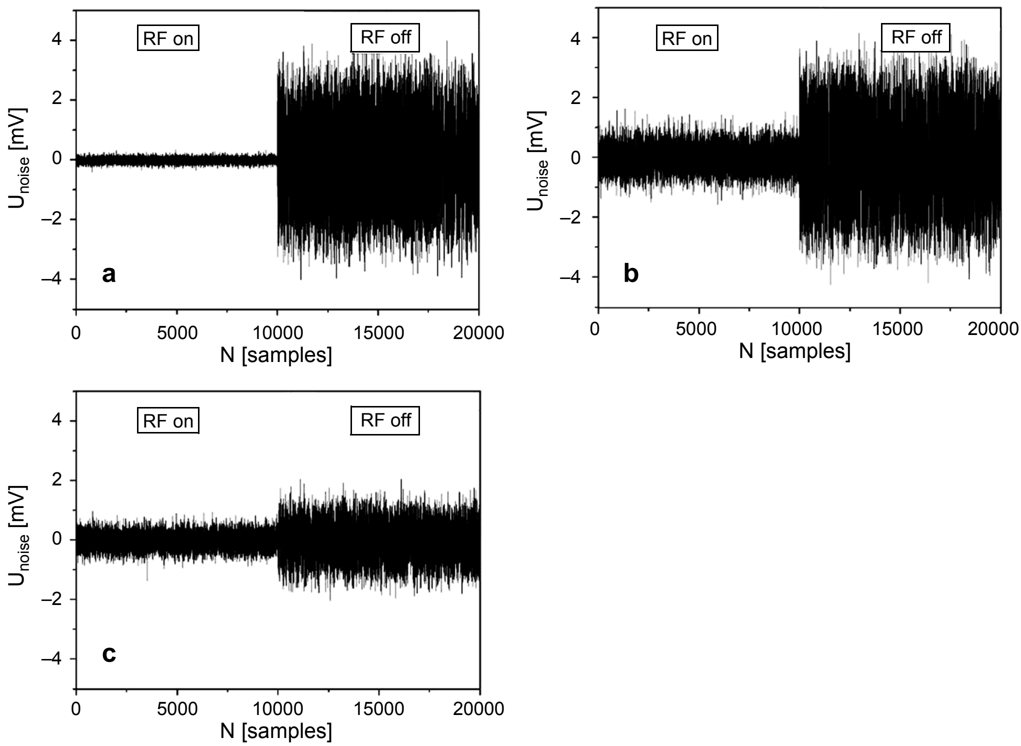


Fig. 6. Influence of the RF modulation on the LD noise performance for LD DC power of 3 mW (**a**), 1 mW (**b**) and 0.2 mW (**c**).

For the smaller values of the LD radiation power the intensity noise reduction by the RF modulation was less effective but still detectable.

In Figure 6 we show the performance of the tested LD at the DC power level of 3 mW, 1 mW and 0.2 mW, respectively. It can be clearly seen that there is a decrease in the laser noise when the RF modulation is switched on.

5. SPM noise performance measurements

The best reflection of an impact of the RF current modulation of the LD bias current on the quality of the entire SPM deflection system is the measurement of the system

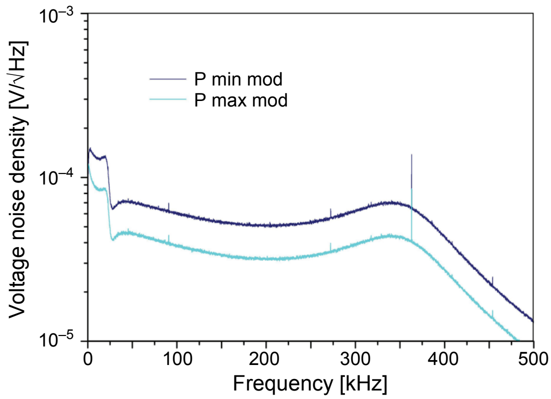


Fig. 7. Spectral noise density of the total signal detected by the photodetector of the tested SPM.

spectral noise density. In our first experiments we observed the SPM deflection signal, which corresponded with the light beam reflected from the stiff micromirror mounted in a sensor head – Fig. 7. It can be seen that the RF modulation decreases by half the noise level detected by the SPM segmented position sensitive detector.

In our next experiments we recorded the spectral noise density of the vibration of the silicon Au coated microcantilever (dimensions: length, width and thickness of 500 µm, 100 µm, 1 µm). The recorded results show the increased signal-to-noise ratio (SNR), when the RF modulation was switched on. The ratio between the resonance peaks and the noise background is considerably higher when the RF current modulation was applied – Fig. 8.

Figure 9 presents results of the measurements of the SPM system, which was developed in our group. In order to avoid heating of the microcantilever, 0.2 mW output power of the LD was defined.

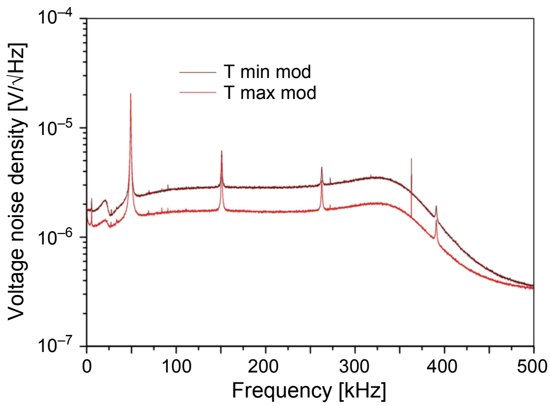


Fig. 8. Vibration spectral noise density of the vibration of the silicon Au coated microcantilever (dimensions: length, width and thickness of 500 µm, 100 µm, 1 µm), the minimum and maximum depth of modulation of the laser diode at a frequency of 300 MHz.

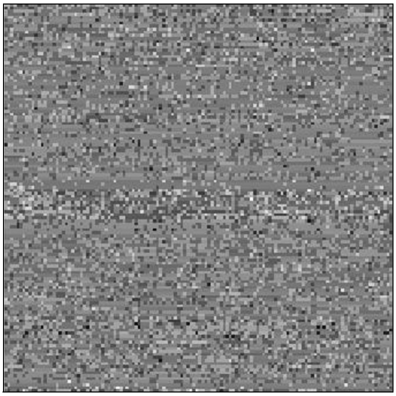


Fig. 9. SPM noise performance-measurement conducted for laser power of 0.2 mW and modulation frequency of 200 MHz.

In our experiments we kept the *X* and *Y* position of the microscope fixed. The force between the cantilever and the surface was controlled and the output signal of the SPM feedback loop was recorded as a measure of system noise performance. To compare noise properties of various set-ups, the root mean square roughness (RMS/Rq) values of the topography data were calculated.

In our experiments we observed Rq of 0.15 and 0.19 for RF modulated and nonmodulated laser diodes respectively, which confirms the ability for noise reduction by the described method.

6. Conclusions

In this paper, the architecture of the RF laser power modulation system was presented. This system was applied to increase the resolution of the cantilever deflection in the homebuilt SPM. The experimental investigation showed an improvement in the noise performance: a considerable decrease in the intensity noise, better than three times, when the optical laser power is above 2 mW, and RF modulation is very effective. In the SPM the head laser diode has 0.2 mW and even for such low power an increase in the noise performance and the Rq parameter reduction were observed.

Acknowledgements – This research was supported by the POIG project *Mikro i Nanosystemy w Chemii i Diagnostyce Biomedycznej – MNS DIAG*, project number POIG.01.03.01-00-014/08-03.

References

[1] GOTSZALK T.P., *Systemy mikroskopii bliskich oddziaływań w badaniach mikro- i nanostruktur*, Oficyna Wydawnicza Politechniki Wrocławskiej, 2004, pp. 22–97 (in Polish).

[2] GRAY G., ROY R., *Bistability and mode hopping in a semiconductor laser*, Journal of the Optical Society of America B **8**(3), 1991, pp. 632–638.

[3] YAMADA M., HIGASHI T., *Mechanism of the noise reduction method by superposition of high-frequency current for semiconductor injection lasers*, IEEE Journal of Quantum Electronics **27**(3), 1991, pp. 380–388.

[4] FUKUMA T., KIMURA M., KOBAYASHI K., MATSUSHIGE K., YAMADA H., *Development of low noise cantilever deflection sensor for multienvironment frequency-modulation atomic force microscopy*, Review of Scientific Instruments **76**(5), 2005, p. 053704.

[5] DOEV V.S., KOLEDOV V.V., KUKLIN A.YU., *Mode-hopping noise reduction by rf modulation of the pump current of an injection semiconductor laser with an external cavity*, Quantum Electronics **24**(7), 1994, pp. 608–612.

[6] FAKUMA T., JARVIS S.P., *Development of liquid-environment frequency modulation atomic force microscope with low noise deflection sensor for cantilevers of various dimensions*, Review of Scientific Instruments **77**(4), 2006, p. 043701.

Received September 25, 2010