研 究 速 報

Monolithically Integrated Diode Laser Detection System for Scanning Near-Field Optical Microscopy (SNOM): Study of the Optical Feedback Effect in VCSELs

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1. Introduction

The early eighties have witnessed a revolution in the perception of physical phenomena with the birth of a new generation of imaging systems based on the detection of non-radiating fields such as the scanning tunnelling microscope (STM) and the atomic force microscope (AFM). The scanning near field optical microscope (SNOM) is the latest of this family and is based on the detection of tunnelling photons[1]. We propose to fabricate a semiconductor integrated nanoprobe which will further enhance the capabilities of this instrument.

2. Scanning Near-field Optical Microscopy

In optics the impossibility of obtaining subwavelength resolution has been known for a long time. Two point-like objects can be distinguished only if the distance between them is greater than a quantity of the same order as the wavelength of the illuminating light beam, thus limiting the resolution to a few hundred nanometers. This relation known as the Rayleigh criterion has been established assuming propagative waves but if one can detect non-radiating fields one can expect to circumvent the Rayleigh criterion and to overcome the diffraction barrier. In near field optical microscopy the light collector is brought to a distance smaller than half a wavelength from the object. Roughly speaking one can say that the collector captures the field before it propagates.

First the light collector is placed and driven just a few nanometers away from the object without touching it by use of suitable actuators such as piezoelectric motors. Because of this exceedingly small distance between sample and probe the collector is not an imaging system but a point-like detector able to collect the light locally and to convert it into electric current or to re-emit it into free space or through a suitable light guide toward a photodiode. The simplest collector used in a SNOM is the extremity of a tapered optical fibre. Finally, because of local detection, no image can be directly obtained. In order to generate an image-like structure, the collector (the fibre tip) must scan the object surface in the same way as an electron spot scans a TV screen.

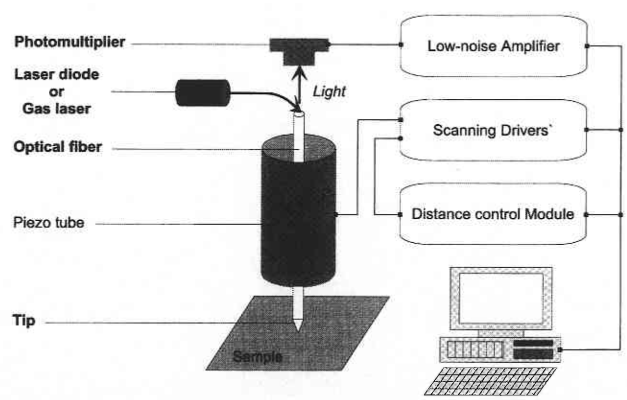

Fig. 1 Schematic diagram of a Scanning Near-field Optical Microscope (SNOM).

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A basic SNOM system, schematically described in Fig. 1, is mainly composed of (1) a laser providing the incident light beam which is converted into propagating components able to propagate towards the detector and evanescent ones confined to the surface which exhibit strong local variations over distances much smaller than the wavelength and (2) a tapered fibre tip able to collect photons, to convert the evanescent field into a propagating field and to transmit it to (3) a remote detector which amplifies and converts it into electric current.

3. Integrated System

We propose an integrated nanoprobe performing the functions both of light emitter and near-field detector. The key element of this novel system, presented in Fig. 2, is a vertical cavity surface-emitting laser (VCSEL), operating at 780 nm, with a PIN photodetector integrated into the back of the VCSEL structure. On top of the VCSEL a conical structure fabricated by specific wet etching, with the radius of curvature at the tip lower than 50 nm, acts like the tapered extremity of an optical fibre. The light beam emitted by the tip will be reflected by the sample and then backscattered by the tip into the laser cavity. "Self-mixing interference" occurs between the light inside the laser cavity and the reflected light which results in a power modulation that can be detected by the photodetector mounted on the backside of the laser. This photodetector monitors the laser output power emitted from the rear of the VCSEL. The proposed system will be experimentally validated by examining thin film materials affected by optical inhomogeneities (refractive index, reflectivity, thickness and topographic variations). Advantages of the proposed type of

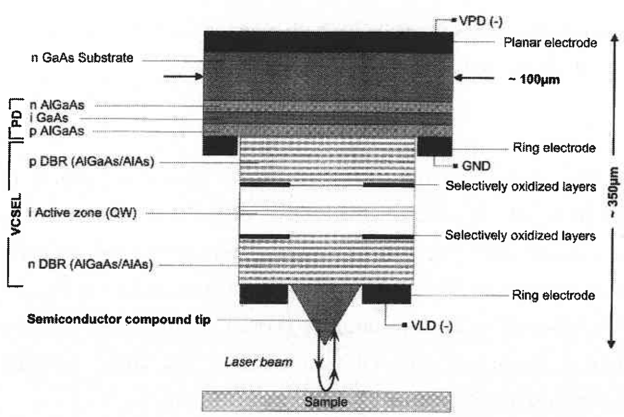

Fig. 2 Monolithic detection system integrating the 3 main elements of a near-field optical microscope i.e. light source (VCSEL), photodetector (PD) and nano-collector (tip) whose names are written in bold on Fig. 1.

detection are compactness, array fabrication at low cost and the possibility of spectroscopic analysis in the range of several nanometers by changing the temperature or current of the VCSEL.

4. Study of the optical feedback in VCSELs

The behaviour of a laser diode is on one hand seriously affected by unintentional optical feedback[2]. But on the other hand controlled external feedback is potentially of practical use: when a small portion of light returns into the laser cavity and is mixed with the original oscillating wave a phenomenon called "self-mixing interference" occurs between the light inside the laser resonator and the light which has been emitted by the laser and then reflected from the external mirror back into the laser cavity. In near-field detection the external cavity will be the combination of the tip extremity and the surface of the sample to be measured[3]. The tip-sample combination acts as an external cavity mirror whose reflectivity depends both on the optical properties of the sample and the nanometer range distance between the tip and the sample[4].

Our goal is to demonstrate the hypersensitivity to very weak local variations of reflectivity of near-field detection based on the self-mixing interference effect in VCSELs. We first investigated this effect in conventional edge emitting laser diodes in which this phenomenon has been known for a long time, mainly in far-field detection where high sensitivity to feedback levels lower than 10^{-6} can be obtained[5]. We then studied prototype VCSELs provided by T. Kagawa and K. Tateno from NTT Opto-electronics Laboratories (Atsugi, Japan).

The experimental set-up we used to investigate optical feedback in VCSELs is presented in Fig. 3. The cleaved extremity of a single-mode optical fibre plays the role of external reflector. It is held

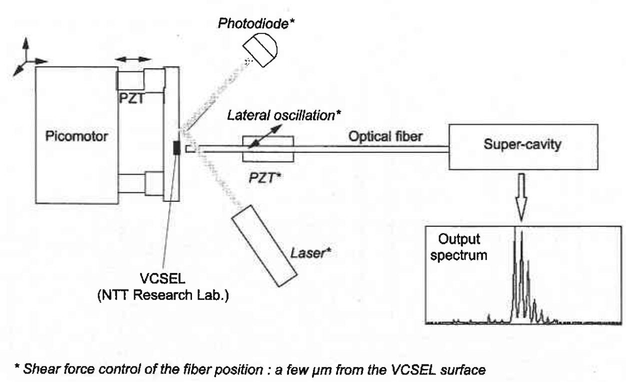

Fig. 3 Experimental set-up used to investigate optical feed-back in VCSELs.

a few micrometers from the VCSEL output by using a shear force detection system. The light emitted from the VCSEL is reflected by the cleaved facet of the fibre and sent back into the laser. The amount of light re-injected into the laser cavity depends on the distance between the fibre facet and the VCSEL surface. The emitted light is collected by the same fibre and sent to an optical power detector or a Newport SuperCavity optical spectrum analyser, a Fabry-Perot resonant cavity with a finesse greater than 27000 i.e. a resolving power of 5×10^{-4} nm.

We tested VCSELs operating at 840 nm with a maximum output power of 7.4 mW for an injected current of 50 mA. In Figure 4 are presented L-I characteristics of a single VCSEL for two different but very close levels of feedback. Both the threshold current of the laser diode and the slope of the emission curve beyond threshold are modified when a slight change in the feedback level occurs. The principle of active near-field detection is based precisely on this modification of laser emission parameters[4].

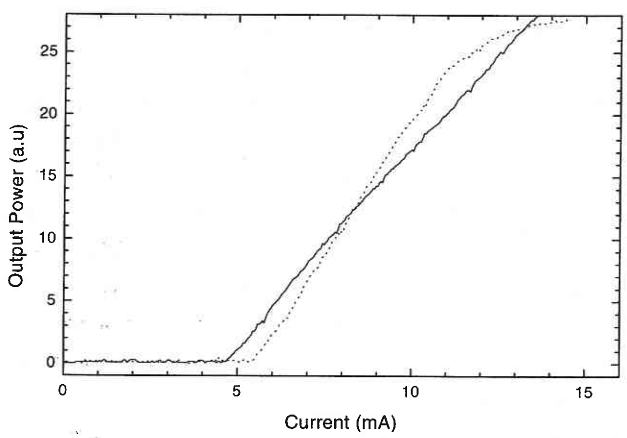

Fig. 4 Variations of the laser diode output power for a modulation of the mirror position.

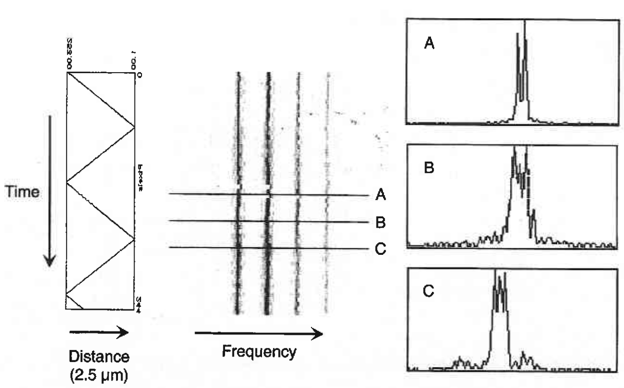

Fig. 5 Variations of the laser diode output spectrum for a modulation of the mirror position.

We then investigated the effect on the output spectrum of small variations of the fibre position for a weak optical feedback level. The VCSEL-fibre position was modulated with an amplitude of 2.5μm and the resulting modifications of the emission spectrum are presented in Fig. 5. Both position and shape of the emission peak vary according to the external reflector position and thus according to the amount of optical feedback.

In conclusion we have experimentally verified that VCSELs have a sensitivity to external optical feedback similar to that of conventional edge emitting laser diodes. This can be attributed to the photon lifetimes being similar in the two devices despite their very different structures.

Indeed edge emitting laser diodes have long optical cavities (200-500μm) and low facet reflectivity (~30%, up to 90% with additional coating) whereas VCSELs are characterised by very short optical cavities (~1μm) and high facet reflectivity (>99%). The combination of these two parameters results in the photon lifetime in VCSELs being in fact very similar to that in edge emitting laser diodes. As a consequence of the high facet reflectivity only a small portion of any feedback from an external reflection can re-enter a VCSEL. It might be thought that this would give VCSELs a very good immunity to optical feedback. The feedback rate into the laser is given as k_{ext} / L with k_{ext} being given by $k_{ext} = (1 - r_2^2)\, r_3\, \eta / r_2$. L is the length of the laser cavity, r_2 and r_3 are the laser facet and external field reflectivities and η is the coupling coefficient between the external mirror and the laser. The value of k_{ext} / L is the same for VCSELs and for edge emitting laser diodes. The effect of the high facet reflectivity is effectively cancelled by the small cavity round-trip time, and the amount of external light injection per round-trip of the internal laser cavity is thus the same for both types of lasers, hence the similar feedback sensitivities[6].

5. Conclusion

The results of the investigation of optical feedback in VCSELs are very encouraging and we intend to use the self-mixing interference effect as the working principle of the optically active near-field detection system presented in part 3 (cf. Fig. 2). The study of VCSEL technology carried on in parallel with the former should lead to the fabrication of a VCSEL array, operating at 950 nm in pulsed operation, in the near future[7].

We will then focus on the fabrication of III-V compound sharp tips by use of techniques inspired by the work performed by other research groups on Silicon or GaAs tips for AFM and STM applications[8,9]. The integration of such a tip with a VCSEL without degradation of either of the two components is a real challenge. However the resulting nanoprobe should be a breakthrough in near-field scanning optical microscopy.

Acknowledgements

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