International Conference on Space Optics—ICSO 2000
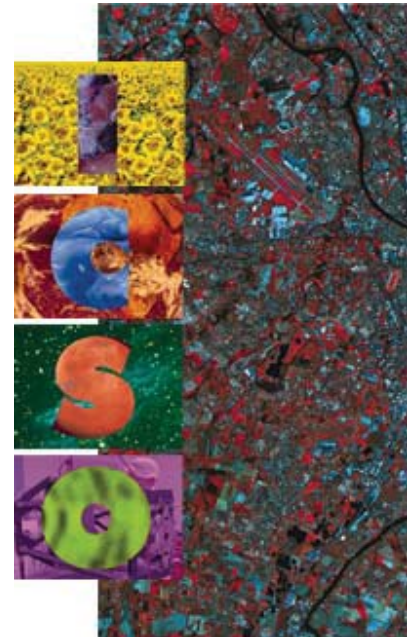
Toulouse Labège, France

5–7 December 2000

The potential of diffraction grating for spatial applications

Y. Jourlin, O. Parriaux, F. Pigeon, A. V. Tischenko

THE POTENTIAL OF DIFFRACTION GRATING
FOR SPATIAL APPLICATIONS

Y. JOURLIN, O. PARRIAUX, F. PIGEON, A.V. TISCHENKO

Laboratoire TSI, Université Jean Monnet, F-42023 Saint-Etienne
Fax : +33477485120, Phone : +33 477485162, E-mail : parriaux@univ-st-etienne.fr

RESUME – *Les réseaux de diffraction sont connus et sont fabriqués depuis plus d'un siècle. Ces composants sont à nouveau d'actualité, et ce pour deux raisons : Premièrement parce qu'ils sont maintenant mieux compris, ce qui conduit à une exploitation efficace de ce que l'on appelait jusqu'ici leurs « anomalies ». Deuxièmement parce qu'ils peuvent être fabriqués avec les moyens du potentiel industriel moderne des technologies planaires. Ces nouveaux réseaux offrent maintenant de meilleures performances que les réseaux conventionnels et abordent des champs d'application nouveaux qui n'étaient pas attendus. C'est le cas des applications au domaine de l'espace où ils peuvent offrir de multiples fonctions optiques, petite taille, faible poids et robustesse mécanique. L'article proposé commentera brièvement l'utilité des applications spatiales de la diffraction. Une des plus importantes applications concerne la mesure de déplacement. Les capteurs de translation et de rotation habituels sont des dispositifs volumineux. Leur utilisation au sein d'un système implique donc souvent la re-définition du système et des assemblages lourds et gênants. Nous proposons une version miniaturisée de la traditionnelle technique des réseaux en mouvement utilisant des réseaux submicroniques et un OptoASIC spécifique qui permet à la fonction de mesure d'être discrète une fois insérée dans des systèmes électromécaniques légers et compacts. La résolution nanométrique est possible sans compromis sur la longueur de l'échelle de mesure. Une autre famille d'application spatiale touche le domaine des spectromètres où les nouveaux types de réseaux permettent un traitement plus flexible du spectre optique. Une autre famille d'applications aborde la question des communications entre satellites : l'introduction de réseaux dans les cavités laser où dans les miroirs laser permet la stabilisation de la polarisation émise, la stabilisation de la fréquence ainsi que le balayage sans parties mobiles d'une large échelle de fréquences.*

ABSTRACT – *Diffraction gratings are know, and have been fabricated for more than one century. They are now making a come back for two reasons: first, because they are now better understood which leads to the efficient exploitation of what was then called their "anomalies"; secondly, because they are now fabricable by means of the modern manufacturing potential of planar technologies. Novel grating can now perform better than conventional gratings, and address new application fields which were not expected to be theirs. This is the case of spatial applications where they can offer multiple optical functions, low size, low weight and mechanical robustness.*
The proposed contribution will briefly discuss the use of gratings for spatial applications. One of the most important applications is in the measurement of displacement. Usual translation and rotation sensors are bulky devices, which

impose a system breakdown leading to cumbersome and heavy assemblies. We are proposing a miniaturized version of the traditional moving grating technique using submicron gratings and a specific OptoASIC which enables the measurement function to be non-obtrusively inserted into light and compact electro-mechanical systems. Nanometer resolution is possible with no compromise on the length of the measurement range.

Another family of spatial application is in the field of spectrometers where new grating types allow a more flexible processing of the optical spectrum.

Another family of applications addresses the question of inter-satellite communications: the introduction of gratings in laser cavities or in the laser mirrors enables the stabilization of the emitted polarization, the stabilization of the frequency as well as wide range frequency sweeping without mobile parts.

1 – INTRODUCTION

It may look somewhat inadequate to report on a particular optical component in a conference devoted to aerospace techniques and systems. Optical gratings have long been around in spectroscopy, spectral analysis, lasers. The interest in gratings has rapidly developed during the last decade as a consequence of the move of planar manufacturing technologies to shorter feature size, of the need of more compact and lower cost opto-electro-mechanical systems, and also of the discovery of new resonant diffractive effects which provide periodical structures with improved characteristics and new functionalities [1].

Diffractive gratings as one of the members of the larger family of Diffractive Optical Elements (DOEs) thus represent an enabling technology for system of smaller size, lower weight, less sensitive to temperature and vibration, more reliable and of lower cost. Such features are highly desirable in aerospatial applications. We are here going to illustrate in two very different examples how optical gratings can help solve technical problems which can be met in aerospace. The first one is an example of displacement measurement function integrated into mechanical modules. The second one is an example of how a grating can stabilize the polarization of a microchip laser for inter-satellite communications.

2 – OPTICAL GRATINGS FOR NON-OBSTRUSIVE DISPLACEMENT MEASUREMENT

The usual breakdown of a monitored (electro)mechanical translation or rotation module is composed of three parts: the fixed mechanical part, the moving part, and the measurement system. The latter is in turn composed of at least three parts : the intelligent part comprising a light source, detectors and means to encode the displacement (usually two or three gratings), and two parts mobile relative to each other which will be fixed onto the module to be monitored with well defined standards. This is industrially correct but represents a practically stiff and unwieldy solution. There are applications and markets where the price to pay in term of weight and size is too large. Aerospace is one of them. The alternative solution is to get rid of the supplementary mechanical parts and constraints related which the displacement sensor by itself represents, and to adopt instead a concept whereby the displacement measurement function is inserted non obtrusively into the (electro)mechanical system in the form of a miniaturized optical element without imposing constraints to the designer. One condition for this is the miniaturization of the read head . One further advantageous consequence of the read head being insertable into the core of the (electro)mechanical system or module is that this enables the measurement to be made where the

displacement actually takes place, i.e., before elastic strains, backlash and frictions distort the desired information.
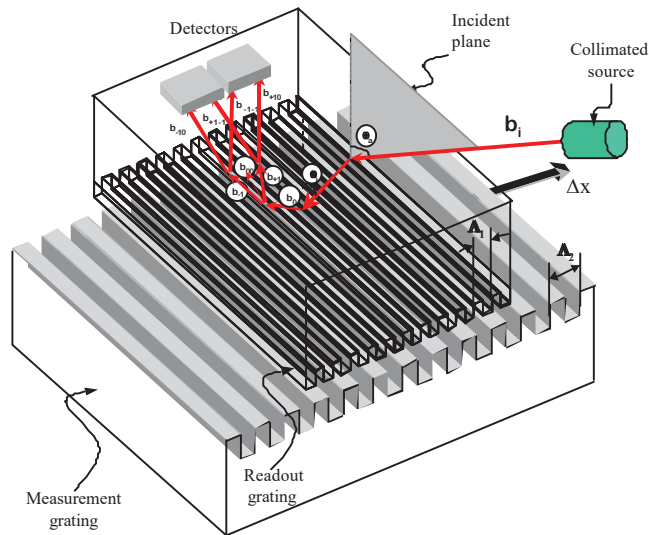

Figure 1 : Perspective view of a miniaturizable translation sensor with oblique incidence using two gratings in a period ratio of 2

Figure one is the illustration of one of the possible embodiments of the basic principle of diffractive interferometry[2] whereby the collimated beam of a semiconductor laser crosses the readout grating a first time, then gets diffracted into the +1 and –1 reflected orders by the moving measurement grating. The latter are both diffracted into the 0th and the $–1^{st}$ transmitted orders of the readout grating. The spatial period Λ_1 of the readout grating is smaller than the beam wavelength λ so that there is no transmitted diffraction order except the 0th order under normal incidence from the substrate side. If the period Λ_2 of the measurement grating is exactly half that of the readout grating, the latter acts as a recombining element projecting the beams back-diffracted by the measurement grating onto each other in two directions where they interfere. Two detectors placed at the back side of the readout grating substrate at a distance where the two interfered beams have separated spatially detect the interference products. The interference products depend on the phase between the two interfering orders emanating from the measurement grating. If the incidence is normal, the phaseshift only comes from the lateral displacement of the measurement grating with respect to the read head , or conversely. It is knows that the phase-shift $\delta\varphi$ experienced by a wave diffracted in the order m of a moving grating of period Λ over the displacement Δx is $\Delta\varphi = mk_g \Delta x$ where $k_g = 2\pi/\Lambda$ is the grating spatial frequency. Refering now to figure 1, the phase-shift $\Delta\varphi$ between the two beams of order + and – 1 diffracted by the measurement grating having moved by Δx is $\Delta\varphi = 2k_{g2} \Delta x$ where $k_{g2} = 2\pi/\Lambda_2$. The optical power detected by the detectors is composed of a DC term plus the interesting $\Delta\varphi$-dependent AC term. The electrical period of the AC term is exactly half that of the measurement grating, $\Lambda_2/2$. The readout grating can be advantageously composed of two sub-gratings of identical period Λ, but displaced by $\Lambda_1/4$ relatively to each other. Four detectors suitably placed around the grating at the backside of its substrate provide four sinusoidal electric signals of $\Delta\varphi$ in quadrature which allows displacement direction detection and fine interpolation. Taking as an example $\Lambda_2 = 1\mu m$, $\Lambda_1 = 0.5\mu m$ (the wavelength can preferably be between 600 and 800 nm) a displacement resolution of 125 nm is obtained by just counting the zero crossings of the sine and cosine signals.
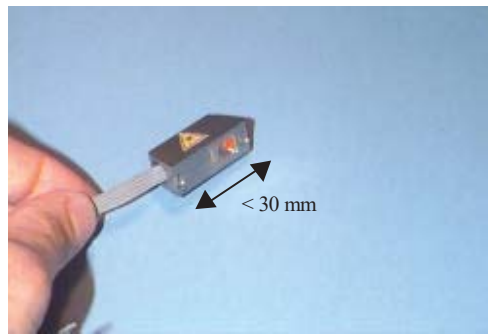
Figure 2 : Encapsulated read head of the type depicted in figure 1 containing a laser, the readout grating and an opto ASIC signal processing

Figure 2 is the picture of a particular embodiment of the described principle on the way towards miniaturization. Its 2.5 cm^3 volume contains a laser diode with oblique incidence, the readout grating, four detectors and elementary signal conditioning. The module is designed so as to incorporate an Opto Asic performing the photodetection, the signal processing and fringe counting as well as interpolation. The OptoASIC will be described in a later paper; early experimental characteristics will be presented at the conference. For proper operation and exact displacement measurement the two gratings must be properly adjusted. The measurement is independent of the grating spacing but a strict parallelism must be ensured between them. Roulis is not a matter of concern and the effects of pitch are usually kept under control by a conventional translation mechanics. The most critical displacement characteristics is the yaw which causes a cosinus error but more importantly leads to a fading of the interference signal picked up by the detector due to the formation of fringes on its surface. Typically, the parallelism between the lines of the two gratings must be kept within a few minutes of arc. Interestingly, the tolerance increases with the miniaturization of the read head.
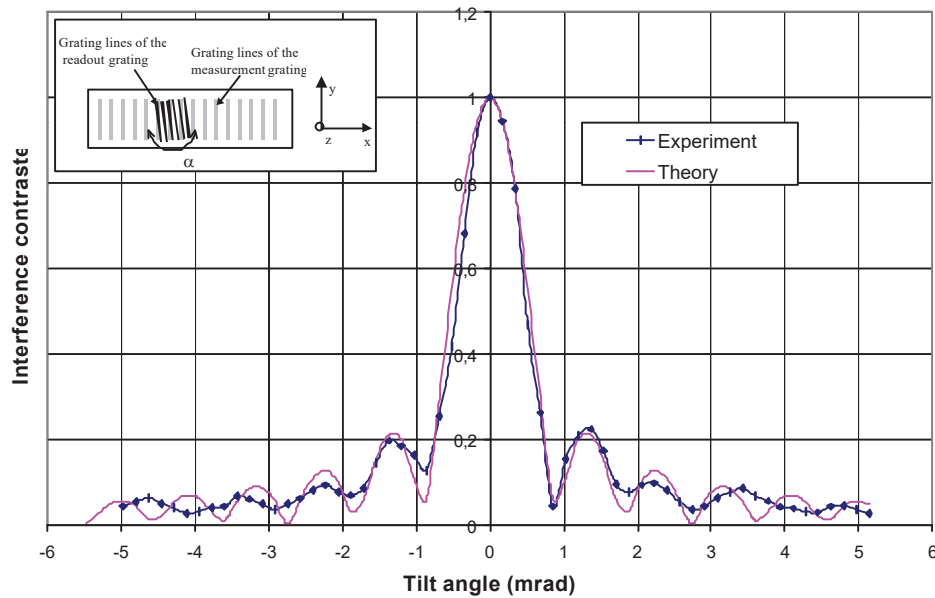

Figure 3 : Dependence of the interference contrast on the tilt angle between the lines of the two parallel gratings

Figure 3 illustrates the measured signal contrast versus the angle between grating lines. The miniaturization potential of this detection principle is high depending on the type of implementation. A LED can be used instead of a laser[3] and an OptoASIC can dramatically reduce the number of parts and the weight of a sensor system. As soon as the main parts of the system (the readout and measurement gratings) can be cheaply and reproducibly produced in the form of small items, this measurement technique can be given a large number of diversified applications where

the measurement function must be performed non-obstrusively where the displacement actually takes place.

3-A GRATING STABILIZES THE POLARIZATION OF MICROCHIP LASERS

A second, completely different, application example shows how a grating can monolithically perform a polarizing function on the emission of an otherwise arbitrarily polarized laser. Microchip YAG lasers for instance appear to be light sources exhibiting all together a number of practically very interesting characteristics and are bound to satisfy the needs of a very diverse and large market[4]. One important function can so far not be performed in a monolithic form. It is the polarization control of the emission. Polarization must be stabilized in many applications such as interferometry, nonlinear effects such as second harmonic generation, parametric oscillation, and coherent communications just to quote a few. We show here that an extra-cavity waveguide grating added to the standard multilayer laser coupler can under a proper design lead to a sufficiently strong difference of reflection coefficient between the selected and undesired polarization[5]. This can advantageously replace the cumbersome stress induced birefringence exerted externally onto the laser crystal. Although the direct advantage of such solution for aerospace is not direct, it illustrates how new types of gratings can perform new functions which their classical countersparts can not.

Its principle relies upon a waveguide grating interference mechanism whereby the reflection of an incident wave at the corrugated surface can be set to between 0 and 100 % by a suitable choice of the structure parameters. The device comprises a Nd : YAG chip, a standard multilayer mirror, a last pair of layers, and a corrugation grating in the last high index layer at the air side as illustrated in figure 4.
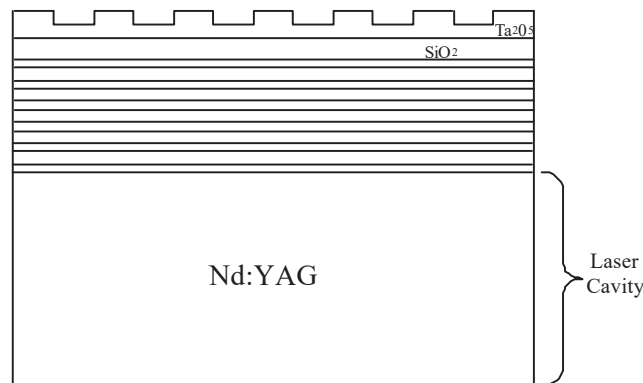

Figure 4 : Multilayer mirror with a polarising corrugation grating in the last high index layer.

The last pair of low and high index layers plays an important role in the polarizing mechanism. It is thicker than the other pairs of layers of the standard mirror. Its optical thickness of λ does not disturb the reflection characteristics which the standard multidielectric mirror exhibits for both incident polarisations. As shown in Figure 5, the grating period is so designed that the undesired TE polarization is coupled into a waveguide mode of the last high index layer and re–coupled into the cavity with a phaseshift of π.
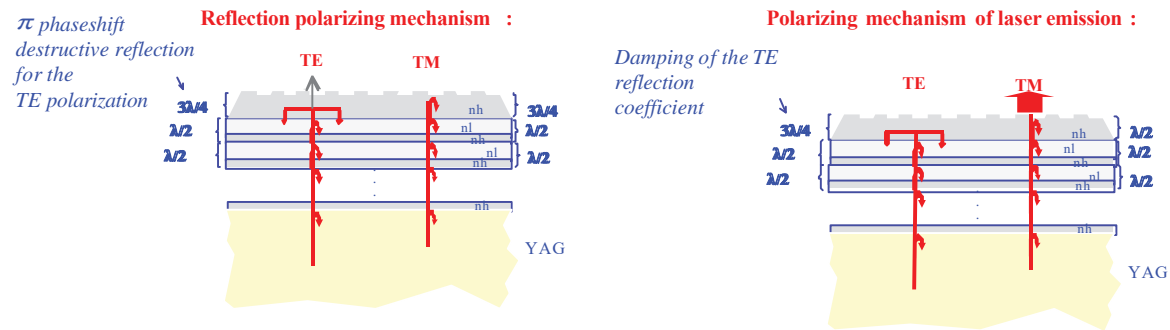
Figure 5 : How a suitably designed grating can induce differential reflection in a multilayer mirror

The grating does not couple the TM polarization into a TM mode of the high index layer because of phase mismatch. The TM polarization therefore does not « see » the grating and experiences the same reflection as if the grating was absent. It does not even diffract into the high index YAG substrate in the form of free space diffraction orders. With a multilayer composed of Ta_2O_5 and SiO_2, the grating period was set to 620 nm and the groove depth to 140 nm (the low index layer has 1.48 index and 180 nm thickness, the high index layer has 2.18 index and 120 nm thickness).

Since the polarizing multilayer mirror is associated with the active medium of the laser cavity, the reflection coefficient differential does not have to be large : a 20 % damping of the reflection coefficient of the undesired polarization is sufficient to prevent its lasing.
Such grating mirror was fabricated by means of direct e-beam writing and RIBE–etched into Ta_2O_5 (Friedrich-Schiller-Universität, Jena) and tested as the output coupler of a microchip Nd : YAG laser. Early results show that the ratio between the TE and TM polarisations is below –17 dB. This demonstrates that a grating can be the integrated element which stabilises the polarisation state of a solid state microchip laser. This implies that manufacturing of polarisation stabilised microchip lasers can be fully achieved by low cost planar technologies. This technique can be applied to pulsed as well as to CW lasers.

4-CONCLUSION

Optical gratings, and to a larger extent Diffractive Optical Elements represent for aerospace applications an enabling technology allowing lower weight, more compact and more reliable optical components, modules and instruments. Two examples of optical grating applications have illustrated the potential of diffractive optical elements for aerospace : the first one deals with displacement sensing where it is shown that very small size and light weight read heads can track the relative movement between mechanical parts where the later takes place and without the need of bulky and heavy interface parts. The second one illustrates how a monolithic diffraction grating integrated to a light source can improve its emission characteristics with more reliability than the state of the art.
Beyond these two examples much more could be said about the potential of more general DOEs with higher level functionality for aerospace, the key words being small size, low weight and high reliability.

REFERENCES :

[1]   Tishchenko A. V., Salakhutdinov I. F., Sychugov V. A., and Parriaux O., 'High-efficient dielectric diffraction gratings for laser resonators', Photonics West, San Jose, 24-30 Jan. 1998, conference 3291, paper 21.

[2]   Voirin G, Benner U, Clube F, Darbellay Y, Parriaux O, Schneider S, Sixt P., 'Performance of interferometric rotation encoder using diffraction gratings', SPIE Proceeding 1997; 3099; 166-175.

[3]   Spies A., 'Linear and angular encoders for the high-resolution range', Progress in Precision engineering and Nanotechnology. Proceedings of the 9th International Precision Engineering Seminar, Braunschweig, Germany, 26-30 May 1997.

[4]   D. Guillot, 'Passively Q-switched micro-lasers make their marks', EuroPhotonics, p. 42, Aug/Sep. 1997. D. Guillot, 'Microlasers: Short Pulses Increase Applications, Photonics Spectra, p. 143, Feb. 1998.

[5]   F. Pigeon, O. Parriaux, Y. Ouerdane and A. V. Tishchenko, 'Polarizing grating mirror for CW Nd:YAG microchip lasers', IEEE Photonics Technology letters, June 2000, Vol. 12, n. 6, pp. 648-651.