9.1 Introduction

Magnetostrictive materials are currently of great interest due to their application potential in sensors and actuators [96,184,185]. Highly magnetostrictive materials are useful for ultrasound generators, magnetostrictive optical wavelength tuners and magnetostrictive delay lines [186]. Some of the requirements for practical applications of magnetostrictive materials include the capability to provide high saturation magnetostriction at low applied fields, ease of fabrication and low cost.

Fe-Ni based amorphous alloys are the best known candidates for magnetostrictive sensors because these amorphous alloys exhibit large saturation magnetostriction, high saturation magnetization, low anisotropy energies and low coercivity [187-189]. At present these alloys are available only in the form of ribbons of thickness ranging from 10 to 50 microns. A series of post treatment process such as high temperature annealing and epoxy treatment are further required for amorphous alloy ribbons to be used as sensors. Therefore there are many difficulties in fabricating systems based on amorphous ribbons for micro sensor applications. Magnetoelastic materials in the form of thin films are an alternative to ribbons and they can be integrated easily to MEMS and NEMS [190]. This not only allows the miniaturization of sensor elements, but also enables the same micro-fabrication technologies to be
used in the production of both electronic and magnetic devices. The integration of magnetic components into MEMS (MagMEMS) offers the advantages of implementing wireless technology [191]. In comparison with other MEMS technologies, for example those incorporating piezoelectric materials, MagMEMS offer a high power density, low performance degradation, fast response times and ease of fabrication.

Thin films based on Fe-Ni can be prepared by techniques such as thermal evaporation, electrodeposition, molecular beam epitaxy, pulsed laser deposition and sputtering. Vapour deposition offers a simple alternative to sputter deposition in obtaining thin films of supersaturated solid solutions and other metastable states. The preparation of Fe-Ni amorphous thin films by thermal evaporation is described in the previous chapters and has been reported elsewhere [69,70,88,180,183,192]. The as prepared amorphous magnetic thin films usually present high coercivity due to the stresses in the films. The magnetic property of such films strongly depends on the magnitude of magnetoelastic anisotropies. So the measurement of magnetostriction is also important in the study of the amorphous ferromagnetic thin films.

Optical fibre long period grating (LPG) can be utilized to quantify the magnetostriction in thin films. It is a non destructive technique. Optical fibre long period grating based sensing methods offer other advantages of electromagnetic interference immunity, compactness, ease of fabrication and multiplexing [193].

LPG’s are usually fabricated by exposing the core of a photosensitive optical fibre to a spatially varying ultra-violet beam [194]. Typically, the impinging UV beam is periodic in space and results in a regular pattern of refractive index modulation in the fibre core. For these gratings the energy typically couples from the fundamental guided mode to discrete, forward propagating cladding mode. Each LPG with a given periodicity \( \Lambda \) selectively filters light in a narrow band width centered on the peak wavelength of coupling \( \lambda_c \)[195]
\begin{equation}
\lambda_i = \left[n_{\text{eff}}(\lambda_i) - n_{\text{cladd}}(\lambda_i)\right] \Lambda
\end{equation}

Where $n_{\text{eff}}$ is the effective index of refraction of the propagating core mode, $n_{\text{cladd}}$ is the index of refraction of the $i^{th}$ cladding mode, $\Lambda$ is the period of grating and $\lambda_i$ is the coupling wavelength. The value of $n_{\text{eff}}$ depends on the core and cladding refractive index while the value of $n_{\text{cladd}}$ depends on the core, cladding and air indices. When a tensile stress is applied to the optical fibre long period grating, the periodic spacing changes and thereby causes the coupling wavelength to shift. This provides a sensitive mechanism to measure the stress/strain and also the magnetostriction of a material attached to the fibre grating.

Few reports exist there in the literature describing the possible use of magnetostrictive transducers in fibre optic based sensors [196-198]. Miroslav Sedlar et al. [196] reported the magnetic field sensing properties of ferrite coated single mode optical fibers. Rengarajan and Walser [197] reported the fabrication of a high speed fibre optic sensor for magnetic field mapping. Their magnetostrictive transducer consisted of a multilayer film of Co$_{50}$Fe$_{50}$/Ni$_{80}$Fe$_{20}$. Chen et al. [198] reported the low field magnetostriction in an annealed Co-30% Fe alloy. Thick sheets of Co-Fe were bonded to a fibre Bragg grating sensor for magnetostriction measurements under different external magnetic fields. The majority of the studies concentrated on single mode fibers with an interferometer configuration for sensing the magnetic field. Long period grating based fibre sensors in combination with a magnetostrictive transducer is a better alternative for sensing the parameters such as magnetic field and strain. A survey of the literature reveals that not much work has been done on exploring the possibilities of amorphous magnetic thin film-LPG based magnetostrictive sensors. The combined use of Fe-Ni thin films and an external magnetic field can provide excellent tuning and chirping of long period fibre gratings [199]. The integration of a magnetostrictive material to an optical fibre long period grating can thus find potential
applications in magnetic field sensing, wavelength tunable optical filters and multiplexing devices. Therefore, the integration of Fe-Ni thin films on to an optical fibre long period grating not only enable us in measuring $\lambda_s$ of amorphous thin films but also help us in realizing possible magnetostrictive sensor devices.

The work presented in this chapter focuses on the preparation of Fe-Ni based amorphous thin films and their integration into an optical fibre long period grating for potential magnetostrictive sensor applications. The attenuation band of the Fe-Ni coupled LPG had dependence on the strength of the magnetic field. Field dependent magnetostriction values were calculated from the shift in the central wavelength of the attenuation band. The results are presented here.

**9.2 Experiment**

Fe-Ni thin films of around 100 nm thickness were deposited simultaneously on to a silicon substrate and an optical fibre long period grating employing thermal evaporation technique. Commercially available Metglas 2826 MB ribbon of composition Fe$_{40}$Ni$_{18}$Mo$_4$B$_{18}$ was employed as a source material to deposit Fe-Ni thin films. The films were deposited by thermal evaporation using a current of 25 A at a base pressure of $1 \times 10^{-5}$ mbar. The base pressure of $1 \times 10^{-5}$ mbar was achieved by a diffusion pump backed with a rotary pump. Room temperature magnetization measurements were carried out using a vibrating sample magnetometer (DMS 1660 VSM) with an external field varying from $-2$ to $+2$ kOe. Magnetostriction was measured by using an instrument with an optical fibre long period grating device, as shown in figure 9.1, in which the shift in the coupling wavelength due to the magnetostrictive strain was obtained using optical spectrum analyzer (YOKOGAWA, Model AQ6319) with a wavelength resolution of 10 pm. LPG was realized by exposing a photosensitive fibre, Newport F-SBG-15 to an excimer laser operated at
248 nm. Point to point technique was used for writing the grating and the grating period was 575 \( \mu m \). The grating was written over a length of 2 cm.

![Fig 9.1 Schematic of the experimental set up for measuring magnetostriction](image)

### 9.3 Results and discussions

Figure 9.2 shows room temperature hysteresis loop for thin film in parallel field. The saturation magnetization was found to be 865 emu/cc and the saturation was achieved at a field of 1000 Oe. The coercivity was \( \sim 60 \) Oe. Even in the absence of crystalline anisotropy, the origin of coercivity can be due to magnetoelastic anisotropies arising from stresses in the film.

In order to gain further insight into the magnetostrictive properties of the film, the magnetostriction was determined at various magnetic fields. The magnetostriction was measured by using an instrument with an optical fibre grating device, as shown in figure 9.1. The shift in the coupling wavelength due to the magnetostrictive strain was obtained with an optical spectrum analyzer.

For long period gratings, the energy typically couples from the fundamental guided mode to discrete, forward propagating cladding mode. The energy transferred to a cladding mode is then absorbed in the protective coating elsewhere in the fibre, which gives rise to an absorption band in the transmission spectrum of a fibre containing such a grating. The peak wavelength of absorption is defined by equation (9.1). When
a tensile stress is applied to the optical fibre long period grating the periodic spacing changes and thereby causes the coupling wavelength to shift. This provides a sensitive mechanism to measure the stress/strain and also the magnetostriction of a material attached to the fibre grating.

![Fig. 9.2 Room temperature M-H curve for Fe-Ni film in a parallel field](image)

The axial strain sensitivity of LPG’s may be assessed by differentiating equation (9.1) [195]

\[
\frac{d\lambda_i}{d\varepsilon} = \frac{d\lambda_i}{d(\delta n_{eff})} \left( \frac{dn_{eff}}{d\varepsilon} - \frac{dn_{cl}}{d\varepsilon} \right) + \Lambda \frac{d\lambda_i}{d\Lambda} \tag{9.2}
\]

The sensitivity comprises the material effects i.e. the change in fibre dimension and the strain-optic effect as well as waveguide effects arising from the slope of the dispersion term \( \frac{d\lambda_i}{d\Lambda} \).
Fig 9.3 (a) Transmission spectrum at a magnetic field of 160 gauss (b) 500 gauss (c) 1010 gauss (d) 1180 gauss and (e) 1370 gauss. Variation of peak position with applied magnetic field is shown in (f)
When an axial strain is applied to the LPG, the resonant wavelength of the LPG will shift because the $\Lambda$ of the LPG will increase and at the same time the effective refractive index of both core and cladding modes will decrease due to the photoelastic effect of the fibre.

The amount of wavelength shift is given by

$$\frac{\delta \lambda_i}{\lambda_i} = \varepsilon_1 - \left( \frac{n^2}{2} \right) \left[ p_{11} \varepsilon_1 + p_{12} (\varepsilon_1 + \varepsilon_t) \right]$$

Where the principal strains are $\varepsilon_1$ along the fibre axis and $\varepsilon_t$ transverse to the fibre axis. If the strain is homogeneous and isotropic, the above equation simplifies to its more common form

$$\frac{\delta \lambda_i}{\lambda_i} = 1 - p_e \varepsilon \approx 0.78 \varepsilon$$

where the photoelastic contributions are subsumed into $p_e$ which is defined by

$$p_e = \left( \frac{n^2}{2} \right) \left[ p_{12} - \mu (p_{11} + p_{12}) \right]$$

in terms of the fibre Pockel’s coefficients $p_{ij}$ and $\mu$ the Poisson ratio. The photoelastic constant is about 0.22 for a silica fibre. This allows the magnetostriction of the sample ($\varepsilon_s$) to be directly determined by

$$\varepsilon_s = \left( \frac{l_f}{l_s} \right) \varepsilon$$

The factor $\left( \frac{l_f}{l_s} \right)$ is introduced to accommodate the difference in length between the fibre grating ($l_f$) and the sample ($l_s$). In the present experiment we have used $l_f = 2$ cm and $l_s = 2$ cm.

Figure 9.3 (a)-(e) shows the transmission spectra in the wavelength range 1625 nm-1665 nm of the Fe-Ni coated LPG for magnetic fields ranging from 160 gauss to
1370 gauss. The peak position was determined by fitting the experimental spectra using the Lorentzian function (red line in the transmission spectra).

Figure 9.3(f) shows resonance wave length versus applied magnetic field. There is a decrease in the resonance wavelength position from 1643.34 nm to 1643.17 as the magnetic field increases from 500 gauss to 1180 gauss. For higher magnetic fields the change is minimal since the film has reached its magnetic saturation (figure 9.2).

![Graph showing magnetostriction coefficient for Fe-Ni films at different magnetic fields](image)

**Fig. 9.4** Magnetostriction coefficient for Fe-Ni films at different magnetic fields

Magnetostriction values calculated at different fields using equation (9.5) are shown in figure 9.4. The saturation magnetostriction was found to be 130 ppm and the magnetostriction was saturated at fields of ~ 1200 gauss. Although, due to the experimental limitations only 3 data points was generated for demonstrating the magnetostriction exhibited by this material, the saturation magnetostriction achieved at a smaller magnetic field indicates the potential of Fe-Ni based amorphous thin films in magnetostrictive sensor devices. If the strain is amplified, for e.g. by using a multilayer stack of alternative magnetostrictive material (Fe-Ni) and a non-magnetic
thin film, a variety of applications such as wavelength tunable optical signal filter, wavelength channel add/drop multiplexer or a signal compensator is possible.

9.4 Conclusions

Fe-Ni based amorphous thin films were prepared by the thermal evaporation technique. The film was integrated to a long period fiber grating. The central wavelength of the attenuation band in the transmission spectrum of the long period grating decreased with an increase in the magnetic field. This dependence was due to the transfer of strain from film to fiber on application of a magnetic field. The change in the resonance wavelength was minimal once the film achieved its magnetic saturation. The magnetostriction properties exhibited by this film imply the potential application of this material in magnetostrictive sensor devices.