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Ginu Rajan
University of New South Wales, ginu@uow.edu.au

Sunish Mathews
University College London

Dean Callaghan
Dublin Institute Of Technology

Gerald farrell
Dublin Institute Of Technology

Gang-Ding Peng
University Of New South Wales

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Abstract

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Keywords

bragg, grating, devices, surgical, invasive, minimally, force, sensors, polymer, fiber

Disciplines

Engineering | Science and Technology Studies

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Polymer Fiber Bragg Grating Force Sensors for Minimally Invasive Surgical Devices

Ginu Rajan[a]*, Sunish Mathews[b], Dean Callaghan[c], Gerald Farrell[c], and Gang-Ding Peng[a]

[a]School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, Australia
[b]Department of Medical Physics and Biomedical Engineering, University College London, London, United Kingdom
[c]Photonics Research Centre, Dublin Institute of Technology, Dublin, Ireland
*Email: ginu.rajan@unsw.edu.au

ABSTRACT

A feasibility study on using polymer fiber Bragg sensors (PFBG) for providing force feedback to minimally invasive surgical devices is carried out. For this purpose a 3 mm long PFBG is fabricated and characterized for strain and temperature sensitivities. The PFBG sensor is then integrated onto a commercial laparoscopic clip applicator which is used as a proof of concept device. The force characterization of the clip applicator is carried out, with a replica setup which simulates the clip forming process of the device. An original clip is then formed without and with synthetic tissue samples of different hardness. The replica device force profile and original clip forming force profile follows the same pattern and thus the calibration data can be used to calculate the original force exerting on the tissues which can help in optimizing the clip formation process or can be used for providing force feedback capability to the device.

Keywords: Polymer fiber Bragg grating, Laparoscopic clip applicator

1. INTRODUCTION

Minimally invasive surgical (MIS) procedures involving laparoscopic and endoscopic devices are often preferred over traditional open surgery due to a shorter post-operative recovery time and reduced intra-operative complications. Many ongoing research activities are focused on the use of strain/force sensors for the measurement of interaction forces occurring at the instrument-tissue interface of the surgical devices [1]. The use of fiber optic sensors for this application has many advantages over other force feedback sensors such as immunity from electromagnetic interference, MRI compatibility, miniature size etc. Polymer fiber Bragg gratings have attracted much interest among application engineers and scientists due to their unique advantages compared to the silica counterparts, such as the inherent fracture resistance, low Young's modulus, high flexibility, high temperature sensitivity, large strain measurement range, and low density [2-4]. In recent years, advancements in the fabrication of singlemode polymer optical fiber (POF) have also enhanced the research and development of Bragg grating sensors in POF [5]. Given the advantages of PFBGs, it can be considered as a good candidate for sensing applications for minimally invasive surgical devices.

To demonstrate the use of PFBG for sensing applications in MIS devices, a laparoscopic clip applicator is sensorized and its force feedback measurement is carried out. Most of the commercially available handheld laparoscopic surgical devices require the surgeon to manually apply the optimum forces in order perform the surgery. In the case of clip applicators, the surgeon applies the force to form the clip using a firing handle. Such devices do not have a built-in force measurement capability which can accurately determine the force applied to the tissue. Current practice relies on the judgment of the surgeon to ensure that appropriate compressive forces are applied to the tissue during the surgery. The use of a force sensing/feedback system could potentially eliminate the subjective nature of the various surgical procedures employing these devices and ensure that the optimum tissue compressive forces are consistently applied. The general requirements of fiber based strain sensor heads to be employed for this particular application are: miniature size (< 5 mm), high strain/force sensitivity, biocompatibility and the ability to be embedded within the device with no hindrance to the device functionality. In this paper we demonstrate the use of miniature PFBG as a force feedback sensor for use with laparoscopic surgical devices. As an example case we have integrated these sensors onto a commercial endoscopic clip applicator device and its performance is studied.

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2. POLYMER FBG SENSOR PROBE AND ITS CHARACTERIZATION

In order to be used for MIS devices the size of the fiber grating length should also be small enough (< 5 mm) to be fixed onto the miniature end-effector of the device. Therefore polymer fiber Bragg gratings with 3 mm grating length and with peak reflected wavelength circa 1531 nm is fabricated [6]. The polymer fiber was approximately 10 cm long and was glued to a silica fiber pigtail. The grating location was approximately 3 cm from the free end of the polymer fiber. In order to protect the fiber from any damages, a protection tube was also inserted into the polymer fiber as shown in the Fig 1(a). The reflection spectra of a 3 mm PFBG is also shown in the Figure 1(b). For calibration purposes, the strain and temperature sensitivities of the polymer FBG sensor are measured before the sensor is glued onto the device.. In fig 1(c) and 1(d), the strain and temperature responses of the polymer FBG are shown. The polymer FBG shows a strain sensitivity of 1.34 pm/με and a temperature sensitivity of 88 pm/^{0}C.

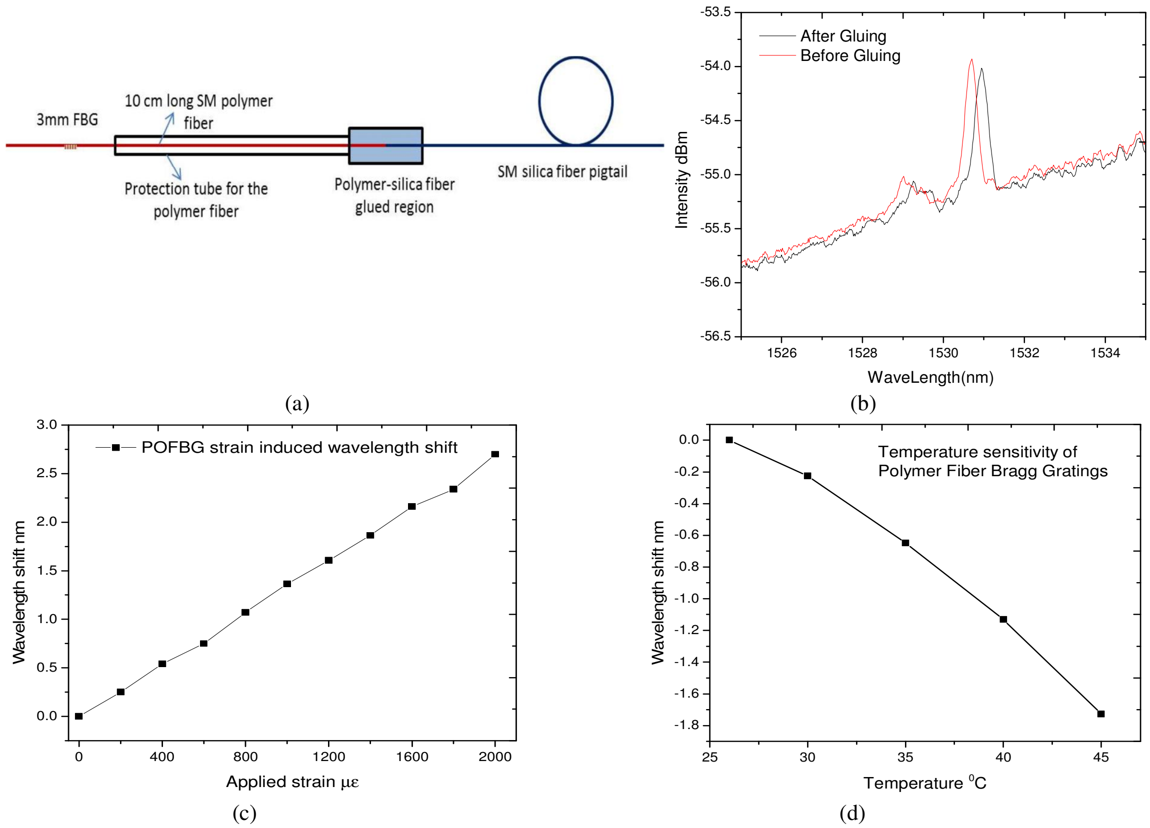


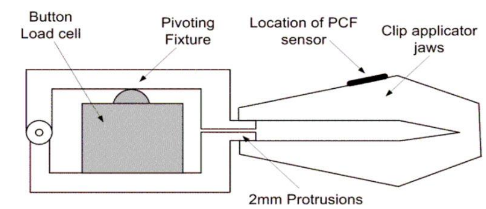
Figure 1. (a) Schematic of the PFBG sensor probe (b) PFBG spectra before and after embedding into the clip applicator (c) Strain response of the PFBG (d) Temperature response of the PFBG.

3. CLIP APPLICATOR EXPERIMENTAL SETUP AND CALIBRATION

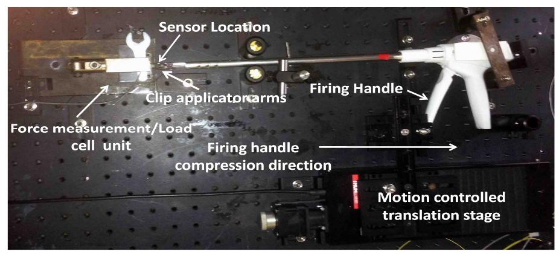
The laparoscopic surgical device used for demonstration is an endoscopic rotating multiple clip applicator, Ligamax (Ethicon Endo-Surgery). The clipping arms of the device are ~ 2 cm in length. A button load cell with a measurement range up to 100 N was used to measure the forces exerted by the arms of the clip applicator during the experimental operation. A pivoting fixture was manufactured to house the load cell and has two 5 mm long protrusions that enable the jaws of the clip applicator to clamp the pivoting fixture and transfer the applied forces to the button load cell. The schematic of the fixture setup is shown in Fig 2(a). The PFBG sensor is attached onto one of the arms at a distance of ~ 1 cm from the tip of the arm. Placing the sensor at this location ensured that maximum sensitivity could be obtained from the sensorized jaw arm when force is applied at its tip. The interrogation of the sensor is carried out using a broadband source and an optical spectrum analyzer, where the reflection spectrum of the polymer FBG is recorded.

3.1. Sensorized Clip Applicator Calibration

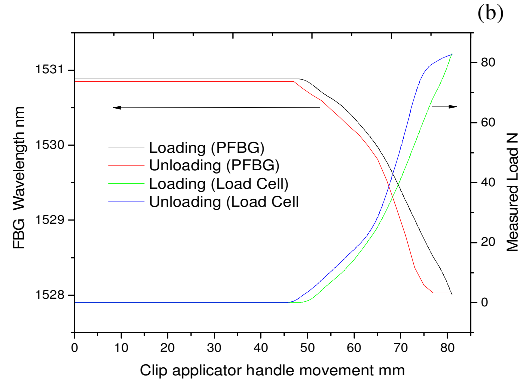
The experimental setup used to perform the strain/force measurement is as shown in Fig 2(b). The device is firmly secured on an optical bench. The firing handle of the clip applicator is compressed by a motion-controlled stage. The total travelling of the handle of the clip applicator is 80 mm, and at approximately 48 mm, the jaws of the applicator touches the protrusions of the pivoting fixture with the load cell setup. This position of the firing handle can be taken as the zero load reference position. The motion controlled stage is then translated in increments of 2 mm from the reference position. The force applied to the load cell by the jaws, for each increment, is measured on a PC (LabVIEW based program) connected to the load cell and the shift in the reflection spectrum of the polymer FBG is also recorded. The translation of the linear stage is stopped whenever the clip applicator indicates to the user (via an audible click) that the maximum force has been applied by the jaws. This occurred when ~ 80 N was applied by the applicator jaws on to the load cell. The FBG sensor experiences a compressive force and exhibits a blue shift as the load increases. The measured wavelength shift and applied load for compression and release of the clip applicator firing handle is shown in Fig 2(c). The compression and release profile is slightly different due to the operating mechanism of the clip applicator. The sensitivity of the sensorized device is measured as approximately 0.088 nm/N. This value is for a contact length of 5 mm of the protrusion, which is similar to the contact region of the clip used in this study.



(a)



(b)



(c)

Figure 2. (a) Schematic of the pivoting fixture to apply jaw forces to the button load cell. (b) Test rig to perform strain/force sensitivity calibration, for the clip applicator device and (c) Measured wavelength shift and load during compression and release of the clip applicator

3.2. Clip formation with and without synthetic tissue samples

The calibrated sensorized clip applicator is used to form clips with and without synthetic tissue samples to understand the force exerting mechanism of the clip applicator for a raw clipping and also for tissues of different thickness. The sample clip used in this experiment, clip loaded in the jaws of the applicator, formed raw clip and clip formed with synthetic tissue sample are shown in Fig 3 (a-d) respectively.

The clips used in this experiment are custom made stainless steel clips. The wavelength shift observed for different clip forming process is shown in Fig 3(e). From the figure it can be seen that the responses follow the same pattern as that of the calibration, but the zero load condition is sustained for a longer handle travelling distance. This is due to the slight mismatch between the calibration setup and the clip used in this experiment. It can be also seen that, the wavelength response are different for different tissue sample hardness. Further work is required to establish an accurate relationship between the wavelength shift, load experienced and the firing handle movement. The aim of this paper is to report the initial results of the study. From the results it can be concluded that, polymer fiber Bragg grating can be a potential sensing solution for MIS devices, and can be widely acceptable to the medical community due to its biocompatibility and benefits from its higher strain sensitivity.

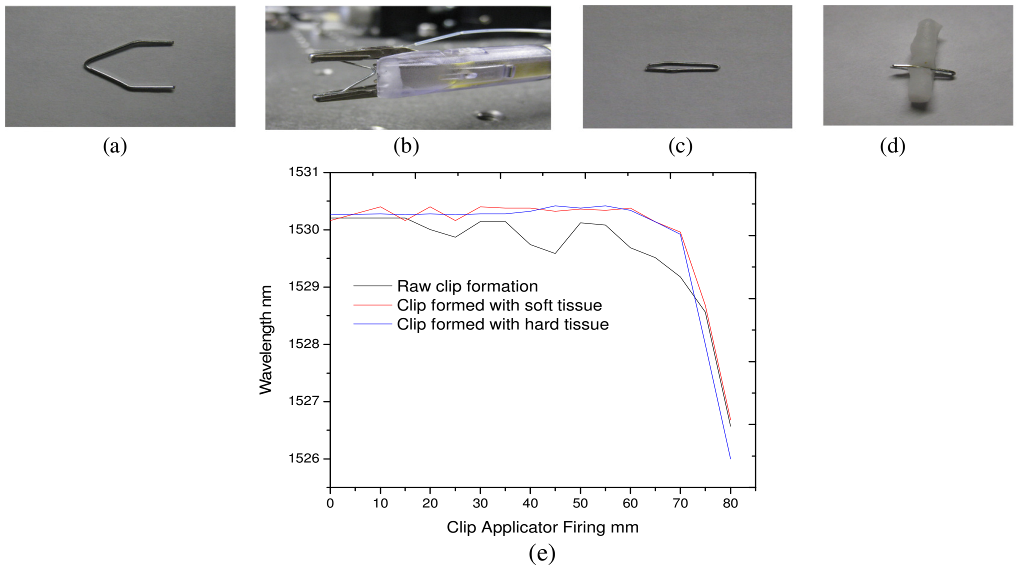


Figure 3. (a) sample clip used in this experiment (b) clip loaded in the jaws of the applicator (c-d) raw clip formed and clip formed with synthetic tissue (e) Measured wavelength shift during the clip forming process

4. CONCLUSION

A feasibility study on using polymer fiber Bragg sensors (PFBG) for minimally invasive surgical devices is carried out. We have fabricated a 3 mm PFBG and have used it to sensorize a commercial laparoscopic clip applicator which is used as a proof of concept device. The force characterization of the clip applicator is carried out, with a replica setup which simulates a clip forming process. An original clip is then formed without and with synthetic tissues samples of different hardness within it. The replica device force profile and original clip forming force profile follows the same pattern and thus the calibration data can be used to calculate the original force exerting on the tissues which can help in optimizing the clip formation process. PFBGs are found suitable for sensorizing MIS devices to provide them with force feedback capability and are found to be a better alternative to standard silica fiber based FBGs and other fibers sensors due to its biocompatibility and higher strain sensitivities.

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