Sensors and Actuators A 183 (2012) 1–10

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Multi-point force sensor based on crossed optical fibers

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ARTICLE INFO

Article history:
Received 3 January 2012
Received in revised form 30 May 2012
Accepted 30 May 2012
Available online 8 June 2012

Keywords:
Multi-point sensor
Force sensor
Bending losses
Optical fibers

ABSTRACT

The objective of this paper is to present a sensor concept based on optical fibers suitable crossed in order to obtain a multi-point force sensor. The working principle exploits the optical power losses due to the fiber bending. The bending losses highly depend on the curvature of the fiber. Firstly, an analytical model that relate bending losses to fiber curvature is introduced and experimentally validated. After the demonstration of the proposed concept potentiality, a design procedure based on the simultaneous use of the analytical model and a Finite Element (FE) model is described. The procedure is experimentally validated for a single crossing of fibers and it is used to realize a complete sensor prototype. Finally, the sensor prototype is experimentally calibrated as a multi-point force sensor.

1. Introduction

In recent years, handheld devices (e.g., mobile phones, tablets, multimedia devices) have become popular due to the increasing number of functionalities and applications that implement with an aesthetic increasingly become slim and miniaturized. To interact with all these features, the user requires a greater variety of user-friendly input devices, such as a mouse, keyboard, touchpad, and touchscreen. In particular, touchscreens and touchpads have rapidly developed in last years together with mobile phones and multimedia devices because of their size limitations. Touchpads began to be introduced in laptops in the late 1980s, becoming in few years an important part of the main input interface of mobile devices. Moreover, since Apple has introduced the iPhone on the market, the user interface is considered a fundamental parameter to make the device appealing to the user. However, most touch devices can measure only the contact point when a user touches the device.

As discussed in [1], the forthcoming touch devices require both the contact point and the contact force component. If an input device can estimate both contact point and force component, an innovative variety of mobile devices can be released with new functionalities and applications. The development of touch sensing devices has been actively ongoing. Touch sensing devices are either of touch panel type or pressure/force sensing type. In case of touch panel, the contact point can be measured with an high sensitivity but the measurement of the pressure/force is difficult. Pressure/force sensors can detect a subtle pressure/force, but the main drawback is that very thick sheet devices are required because of the structural complexity of the sensor. All commercial touchpads belong to the touch panel type and in practice, they estimate only the contact point. Most of the sensors able to estimate both contact point and contact force component are prototypes developed within research activities conducted in the fields of robotics and medical instruments [2–12]. However, the developed tactile sensor prototypes cannot use for handheld devices since they typically are not thin and need to manage an high number of signals (al least one for each measuring point).

In this paper an innovative sensor concept based on optical fibers is presented. The proposed device exploits the optical power losses due to the fiber bending. Additionally, the use of fibers allow to maintain a limited thickness for the sensor. In particular, the fibers are crossed in order to realize a mesh with $n \times n$ measuring points, by using only $2n$ fibers. The obtained prototype is a multi-point sensor which allow to estimate the contact point and the contact force magnitude. Since the sensor concept is based on the optical power losses, first of all, an analytical model for bending losses is introduced and experimentally validated. Then, the proposed concept and its potentiality is presented. A design procedure based on the simultaneous use of the validated analytical model and a Finite Element (FE) model is described. The procedure allows to select the design parameters in order to satisfy the desired sensitivity for the sensor and can be easily adapted to different fiber type. The procedure is experimentally validated for a single crossing of fibers and it is used to realize a complete sensor prototype. Finally, the sensor prototype is experimentally calibrated as a multi-point force sensor.

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http://dx.doi.org/10.1016/j.sna.2012.05.045

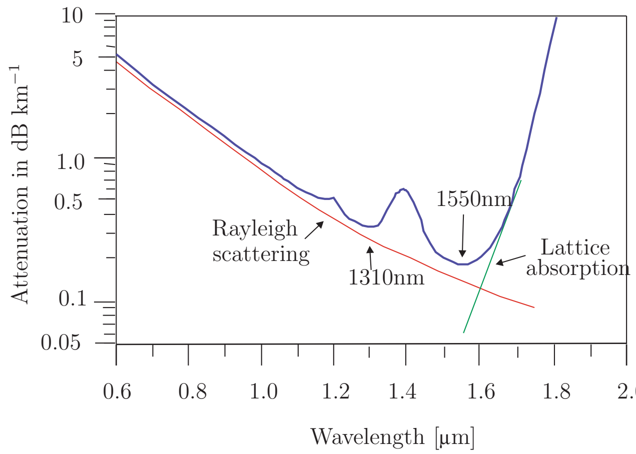

Fig. 1. Attenuation coefficient vs. wavelength in a typical silica based optical fiber.

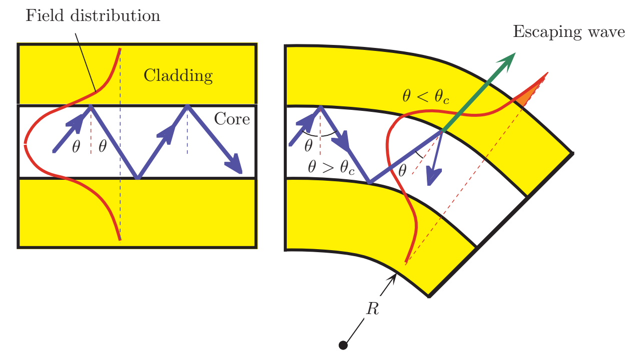

Fig. 2. Bending loss in an optical fiber. A light ray usually reflected at core-cladding interface escapes the core when its angle of incidence θ is inferior to the critical angle θ_c.

2. Bending losses in fibers: model and experimental validation

When light propagates through a material it experiences *attenuation* in the direction of propagation due to different phenomena. At an atomic level *lattice absorption* and *scattering* play a considerable role in signal attenuation, the one prevailing on the other depending on the wavelength, see [13]. We can define an *attenuation coefficient* α as the fractional decrease in optical power per unit distance:

$$2\alpha = -\frac{1}{P(z)}\frac{dP(z)}{dz}, \quad (1)$$

where $P(z)$ is the optical power at point z along the fiber. Integrating the last equation in the interval $[0, z]$ of the guide gives:

$$2\alpha = -\frac{1}{z}\ln\left(\frac{P_{in}}{P(z)}\right), \quad (2)$$

where $P_{in} = P(0)$ is the input power. Inverting Eq. (2) we obtain the useful relation:

$$P(z) = P_{in}\exp(-2\alpha z), \quad (3)$$

which gives optical power at any z as a function of input power and the attenuation coefficient α. A typical silica glass-based optical fiber exhibits an attenuation coefficient similar to the one showed in Fig. 1. Apart from absorption and scattering other factors are also cause of attenuation in optical fibers. The most important are *micro-bending* and *macro-bending losses*. Micro-bending losses are often simply referred to as *bending losses* and are given origin by a local bending of the fiber that allows some of the light energy being guided to escape the core and radiate away through the cladding. More specifically if the curvature radius is such that at some point on the core-cladding boundary the TIR (Total Internal Reflection) condition is not satisfied light rays are refracted and can penetrate the cladding and eventually reach the external coating. The phenomenon is pictured in Fig. 2, where a light ray usually reflected at the core-cladding boundary in absence of bending is instead refracted and lost when the fiber is bent. Bending losses can be modeled with an attenuation coefficient α_B, whose definition is similar to the one of α. The calculation of α_B involves complex analysis of the electromagnetic field propagating in the fiber. Different methods have been proposed, but the usual approach is the formula introduced by Marcuse in [14].

According to Marcuse the attenuation coefficient due to bending losses in a weakly guided fiber is given by:

$$2\alpha_B = \frac{\sqrt{\pi}\kappa^2\exp[-(2/3)\left(\gamma^3/\beta_{mn}^2\right)R]}{\epsilon_m\gamma^{3/2}V^2\sqrt{R}K_{m+1}(\gamma a)K_{m-1}(\gamma a)} \quad (4)$$

where all terms are explained below. Defining with n_1 and n_2 the refractive indices of the core and the cladding respectively and the free-space propagation constant $k_0 = 2\pi/\lambda$ where λ is the wavelength, κ and γ are the field decay rates in the core and cladding:

$$\kappa = \sqrt{n_1^2k_0^2 - \beta_{mn}^2} \quad (5)$$

$$\gamma = \sqrt{\beta_{mn}^2 - n_2^2k_0^2} \quad (6)$$

where β_{mn} is the propagation constant of the LP_{mn} (Linearly Polarized) guided mode in the straight guide. R is the curvature radius of fiber subjected to bending. V is the *V-number* defined as

$$V = \sqrt{k_0^2a^2(n_1^2 - n_2^2)} \quad (7)$$

where a is the fiber core radius. The terms $K_m(x)$ are the second kind modified Bessel functions of order m and argument x. The parameter ϵ_m is defined as:

$$\epsilon_m = \begin{cases} 2 & \text{if } m = 0 \\ 1 & \text{if } m \neq 0 \end{cases} \quad (8)$$

being m the azimuthal mode number of the LP_{mn} mode propagating along the fiber. For the single mode fibers, used in this work, the propagation mode is the LP_{01} and then $\epsilon_m = 2$.

Eq. (4) shows that α_B depends on R and as a consequence, combining Eqs. (4) and (3), the power at the output of a curved fiber of length L and constant curvature radius R can be calculated as:

$$P(L) = P_{in}\exp[-2\alpha_B(R)L], \quad (9)$$

in which explicit dependence from R of the attenuation coefficient is shown. If the stretch of fiber in which light propagates has a variable curvature radius a proper integration of the different contributes to the power losses allows the calculation of the total loss.

The fibers used in this work are the Standard Corning SMF-28, step index single mode fibers. Before using this type of fiber for the proposed sensor design, the model of power losses described above has been experimentally verified. Table 1 reports the physical properties [15] of this kind of fiber at a wavelength of 1550 nm useful for model validation. The power loss has been estimated by using Eq. (9) for different curvature radius R and fiber length L values. The comparison between the model results and the experimental data is reported in Fig. 3 that shows power ratio $P(L)/P_{in}$ as a function of the length L of the fiber. The experimental data have been obtained