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INSIGNIFICANT MACRO-BENDING LOSS OF POLYURETHANE WAVEGUIDES

ROHIT UPPAL

Department of Electrical and Computer Engineering
University of Louisville
KY
USA
e-mail: ruppalul@gmail.com

Abstract

The sensors are embroidered on the robot parts in patterns, which entail bending. The radius of curvature of the bend of the waveguide is larger than the diameter of the waveguide, which may escalate the attenuation. The transmitted intensity through a commercially available multimode waveguide wrapped around mandrels of different diameters was measured with a time-of-flight sensor. I observed that the radius of curvature of the bend is directly proportional to the amplitude of the intensity attenuation. As NA and critical radius of curvature are 0.751 and 694 nm, respectively, bending loss is insignificant. The amplitude of the intensity attenuation increased with the number of wraps.

1. Introduction

Thermoplastic polyurethane waveguides (TPWs) are lightweight, non-

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toxic, corrosion-resistance, highly stretchable, low elastic modulus, insusceptible to electromagnetic interference, and easily manufactured.

Sensors enable soft robots to perceive and respond to manipulate, move, explore, operate, and coordinate [2, 3]. The sensors are embroidered on the robot parts in patterns, which entail bending. The spacing between adjacent turns is larger than the diameter of the waveguide because embroidery machines do not have resolution in the sub-diameter range of waveguides. As the radius of curvature of the bend of the embroidered waveguide is larger than the diameter of the waveguide, in addition to optical losses attributed to absorption, scattering, crosstalk, coupling losses, and parameters of the TPWs, macro-bending losses may contribute to attenuation [4, 5].

The effect of the radius of curvature of the bend on bending attenuation coefficient and core radius on bending loss was studied in [6-8]. The effect of propagation distance on bending loss was studied in [7]. Wavelength, bending angle, and number of wraps affect bending loss [9]. Effect of the wavelength, radius of curvature of the bend and number of wraps has been analyzed in [9, 10].

Effect of the wavelength, radius of curvature of the bend and number of wraps has been analyzed in [10, 11]. A linear relationship was found between bending loss and the number of turns for the large radius of curvature [9]. Bending losses may be neglected beyond a critical radius of curvature (R_c), which is calculated as per equation (1) [12]

$$R_c = 3\lambda n_2 \big/ 4\pi (NA)^3 , \tag{1}$$

where R_c is the critical radius of bending, n_2 is the refractive index of the cladding, NA is the numerical aperture of the fiber, and λ is the wavelength.

Models to calculate the bending loss for optical waveguides have been proposed. A model to calculate bending loss coefficient (2α) of a micro bent fiber was proposed and later modified to include the number of wraps, a fitting function, and V number [8, 13]. A linear relationship was found between bending loss and the number of turns for the large radius of curvature [9].

The optical waveguides will be integrated onto robot surfaces, so in this endeavor, I investigate and analyze the effect of the radius of curvature of the bend as well as number of wraps on optical loss.

2. Materials and Methods

2.1. Commercial optical waveguide

An MH Build series thermoplastic polyurethane multimode waveguide (TPW) with a diameter of $1.75\,\mathrm{mm}$ was purchased from Matter Hackers, CA.

2.2. Characterization of optical loss

One-meter samples of TPWs were wrapped around plastic mandrels (Figure 1). The diameters of the mandrels are $1.27\,\mathrm{cm}$, $2.54\,\mathrm{cm}$ and $5.08\,\mathrm{cm}$. TPWs were connected to a time-of-flight sensor (VL53L0X) from STMicroelectronics, Geneva [14]. It has a vertical cavity surface-emitting laser emitter, that emits a laser $(\lambda = 940\,\mathrm{nm})$. A single photon avalanche diode (SPAD) was applied with a bias voltage of $3.3\,\mathrm{V}$ [14]. The transmitted intensity was measured by the TOF sensor with an Arduino Uno micro controller (Figure 2).

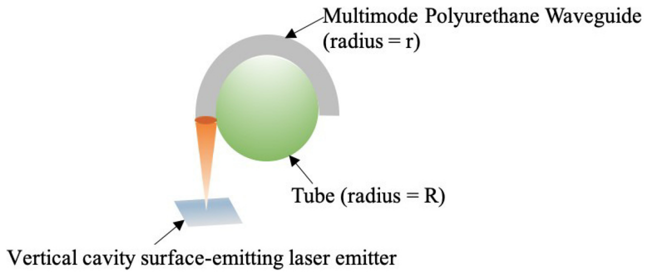

Figure 1. Schematic illustration of an optical waveguide wrapped around a mandrel.

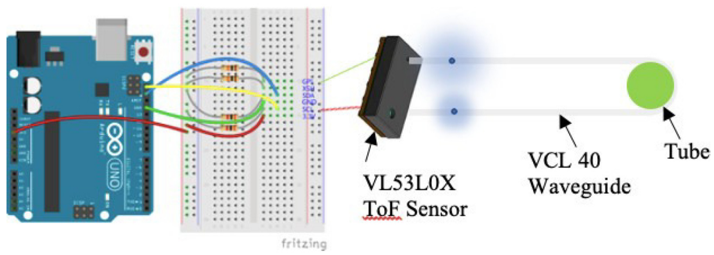

Figure 2. Schematic illustration for computation of the intensity of the loop of a waveguide.

3. Results and Discussions

3.1. Effect of radius of curvature of the bend

The radii of curvature of the bend were varied to observe its effect on the optical loss. As I could not wind four wraps around mandrels with diameter of 5.08 cm, these mandrels were not considered for further experiments. I observed that as the radius of curvature of the bend increases, the amplitude of the intensity attenuation too increases (Figure 3) [7, 8]. It is because, compared to a straight waveguide, fewer effective modes propagate in a bent waveguide (equation 2), thereby causing attenuation.

$$N_{\text{eff}} = N_{\infty}\{1 - \alpha + 2/2\alpha\Delta\,[\,2\alpha/R + (\,3/2n_2kR\,)^{2/3}\,]\}, \tag{2}$$

where N_{∞} = number of modes supported in a straight waveguide; α is the index profile, Δ = core-cladding index difference; n_2 = refractive index of the cladding, $k = 2\pi/\lambda$; R = radius of curvature of the bend.

For a single-mode fiber, the bending loss coefficient (α) can be calculated as given in equation (3) [10].

$$2\alpha = -\,2\kappa^2 lm(\rho)\big/[\,\beta V^2 K_1^2(a\gamma)], \tag{3}$$

where, κ is vacuum wave number at wavelength λ, a is fiber radius, β is the propagation constant of the straight-fiber fundamental mode with infinite cladding, ρ is the amplitude of the backward evanescent field evaluated on the fiber axis, K is the Bessel function, $\gamma = (\beta_0^2 - \kappa^2 n_2^2\,)^{1/2}$, β_0 = unperturbed propagation constant of the straight-fiber fundamental mode with infinite cladding. So, with the increase in fiber radius, bending loss coefficient (α) too increases.

As $NA = 0.751$, hence, the bending loss is insignificant [15, 16]. The bending radii were varied, and the optical intensity was measured. The critical radius of curvature (R_c) is

$$R_c = 3\lambda n_2/4\pi(NA)^3 = 3 \times 940 \times 1.31/4\pi(0.750999)^3 = 694 \text{ nm}.$$

As the radius of curvature of the bend for the TPWs is higher than the critical radius of curvature, bending losses may be insignificant, yet as the radius of curvature of the bend increases, the amplitude of the intensity attenuation also increases (Figure 2) [7, 8].

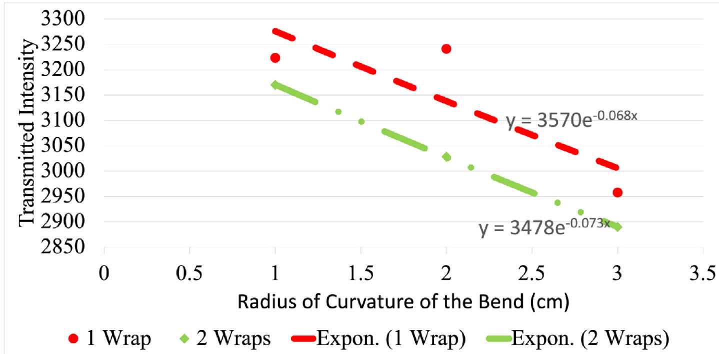

Figure 3. Transmitted intensity with the radius of curvature of the bend.

The transmitted intensity was modeled by a simple exponential relationship.

For one wrap, the model is $y = 3570e^{-0.068x}$.

For two wraps, the model is $y = 3478e^{-0.073x}$.

The slopes of the two models appear to be similar. So, transmitted intensity decreases with the increase in the radius of curvature of the bend at the same rate.

4. Number of Wraps

An increase in the number of wraps has been found to increase the amplitude of the intensity attenuation (Figure 4). A similar linear behavior between loss and the number of turns was obtained in [17]. The bending loss coefficient (2α) increases with the number of turns as given below [8],

$$2\alpha = 2FN[4(\pi)^{1/2}\delta^2 1/\Lambda(n_1k\Delta/b)^2 - \sum J_1^2(J_{1s}b/a)V^{-2}],$$

where N is the number of turns, F is the curve fitting function, a and b are the radius of core and cladding, respectively, n_1 is the refractive index of the core, k is the free space propagation constant, Δ is the difference in the refractive index of the core and cladding, δ is the rms value of extrinsic perturbation amplitude, J_1 (J_{1s}) is the first kind Bessel function of order one and Λ is the spatial perturbation length $(\Lambda = 2R)$.

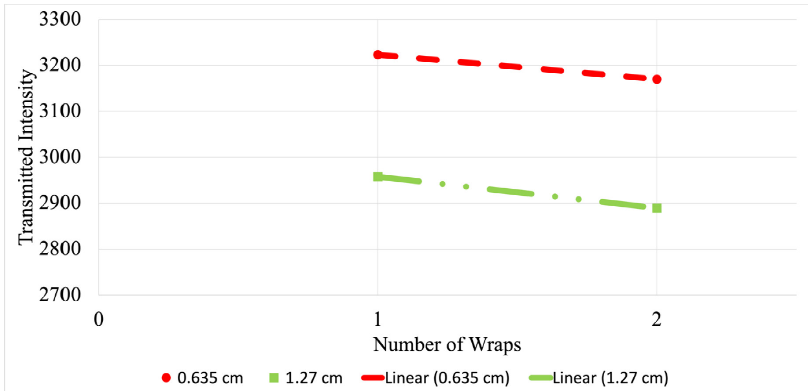

Figure 4. Transmitted intensity with the number of wraps.

5. Conclusion

The radius of curvature of the bend was found to be directly proportional to the amplitude of the intensity attenuation for a polyurethane waveguide. As NA and radius of curvature of the bend are quite high, bending loss is insignificant. A linear relationship was observed between the amplitude of the intensity attenuation and the number of wraps.

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