HE$_{11}$ mode in water-filled hollow core Bragg fiber with a gold layer and dispersive materials

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Abstract

A recent analytical method is used to determine the spectral and amplitude sensitivities for HE$_{11}$ mode in a hollow core Bragg fiber with or without a gold layer when the dispersion relations for all layers are considered. The fiber without a gold layer is made by a water core, surrounded by periodic reflector layers of polystyrene and polymethyl methacrylate with high and low refractive indices, respectively. The thicknesses of the cladding layers are calculated by using the quarter wave condition for two assumed initial bandgap wavelengths ($\lambda_0 = 0.5 \, \mu m$ and $\lambda_1 = 0.68 \, \mu m$). The optical confinement for the HE$_{11}$ mode in the core, at the minimum-loss wavelength, is increased over four orders ($10^4$) of magnitude when a high index material just before the outermost region of a hollow core Bragg fiber is replaced with a gold layer with an optimized thickness. Also, the amplitude sensitivity at the minimum-loss wavelength is increased for an optimized thickness of the gold layer.

1. Introduction

The transfer matrix method has been used extensively for the analysis of the fiber based plasmonic sensors [1–3] and hollow core Bragg fibers [4–8]. Simulations based on the transfer matrix method are validated by the experimental results [6–8]. For a water-filled hollow core Bragg fiber, the geometry of the structure is chosen to have its fundamental bandgap located at the wavelength $\lambda_0 = 0.68 \, \mu m$ [7].

In the recent papers [1–5], our transfer matrix method is applied to some optical fiber where the radial solutions of the Maxwell equations are written as a combination of the Hankel functions $H_1$ and $H_2$ in the gold region. For a hollow core Bragg fiber with or without a gold layer [4, 5], a Hankel function of the first kind $H_1$ is used in the external infinite medium of the fiber. When a high index material just before the outermost region of a hollow core Bragg fiber ($r_c = r_1 = 13.02 \, \mu m, n_c = n_1 = 1, d_{44} = 0.086303 \, \mu m, d_4 = 0.310 248 \, \mu m, n_2 = n_3 = \ldots = n_{34} = 4.6, n_{35} = n_5 \ldots = n_{3N} = 1.6$), with large refractive-index contrast in periodic layers of the reflector cladding, is replaced by a gold layer, the optical confinement for the TE$_{01}$ mode in the core is increased about ten times [4]. If the gold layer is located between the first and the penultimate layer, the loss for the same TE$_{01}$ mode is increased because the parts before and after the reflector gold layer of the fiber are decoupled [4]. The amplitude sensitivity for the leaky core mode HE$_{11}$ near the lowest loss point for the hollow-core Bragg fiber without and with a gold layer increases when the number of the layers increases from $N = 5$ to $N = 11$ [5]. We have demonstrated the accuracy of our method for a hollow core Bragg fiber without a gold layer with $N = 34$ layers (32 reflector layers, 16 pairs), $r_c = 1.3278 \, \mu m, n_c = n_1 = 1, d_{44} = 0.2133 \, \mu m, d_4 = 0.346 \, \mu m, n_2 = n_3 = \ldots = n_{34} = 1.49, n_5 = n_5 \ldots = n_{33} = 1.17$, $\lambda = 1 \, \mu m$, where our effective index $\beta/k = 0.891 067 2175 + 1.422 604 6712 \times 10^{-8} i$ [5] for the TE$_{01}$ mode is very close to $\beta/k = 0.891 067 + 1.4226 10^{-8} i$ calculated in [9].

In this paper we extend the research to the HE$_{11}$ mode of a hollow core Bragg optical fiber when the dispersion of H$_2$O, PS, PMMA and gold layers is considered. The optical confinement and amplitude sensitivity at the minimum-loss wavelength for the HE$_{11}$ mode are increased when the layer with high index just before the outermost region of a hollow core Bragg fiber is replaced with a gold layer with an optimized thickness.
2. HE$_{11}$ mode in water-filled hollow-core Bragg fiber without and with a gold layer

The water-filled hollow-core Bragg fiber with $N = 11$ layers and without a gold layer (figure 1) is made by a water core (refractive index $n_c = n_1 = n_4 = n_{H2O}$ and radius $r_c = 25 \mu m$), surrounded by periodic reflector layers of polystyrene (PS) and polymethyl methacrylate (PMMA) with high ($n_{H1} = n_{PS}$) and low ($n_L = n_{PMMA}$) refractive indices, respectively. The thicknesses of the cladding layers $d_{H1} = d_{PS}$ and $d_L = d_{PMMA}$ are calculated by using the quarter wave condition [10]:

$$d_{PS} = \frac{\lambda_0}{4\sqrt{n_{PS}^2 - n_{H2O}^2}},$$

$$d_{PMMA} = \frac{\lambda_0}{4\sqrt{n_{PMMA}^2 - n_{H2O}^2}}.$$  \hfill (1)

From the relations (1) and (2) we obtain the dependence of $\lambda_0$ on $n_{PS}, n_{PMMA}, n_{H2O}, d_{PS}$ and $d_{PMMA}$ [11]:

$$\lambda_0 = 2(d_{PS}\sqrt{n_{PS}^2 - n_{H2O}^2} + d_{PMMA}\sqrt{n_{PMMA}^2 - n_{H2O}^2}).$$  \hfill (2)

For the theoretical spectral sensitivity $S_\lambda$ [11]

$$S_\lambda = \left| \frac{\partial \lambda_0}{\partial n_{H2O}} \right| = 2n_{H2O} \left( \frac{d_{PS}}{\sqrt{n_{PS}^2 - n_{H2O}^2}} + \frac{d_{PMMA}}{\sqrt{n_{PMMA}^2 - n_{H2O}^2}} \right),$$  \hfill (3)

we must to use $d_{H1}$ and $d_L$ in nm and the result is in nm RIU$^{-1}$. Figure 1 also presents a hollow-core Bragg fiber with $N = 11$ layers and with a gold layer which replaces the layer with high index just before the outermost region.

For a fundamental bandgap wavelength $\lambda_0 = 0.68 \mu m$ we obtain $n_c = 1.330 444 99$, $n_{H1} = 1.584 138 47$, $d_{H1} = 0.197 699 70 \mu m$, $n_{L1} = 1.487 382 80$, $d_L = 0.25 563 947 \mu m$ and $S_\lambda = 1634.67$ nm RIU$^{-1}$. For a non-fundamental bandgap (the lowest loss is larger in comparison to that of the fundamental bandgap) wavelength $\lambda_0 = 0.5 \mu m$ we obtain $n_c = 1.336 335 03$, $n_{H1} = 1.603 276 84$, $d_{H1} = 0.141 109 65 \mu m$, $n_{L1} = 1.495 494 05$, $d_L = 0.186 191 94 \mu m$ and $S_\lambda = 1166.98$ nm RIU$^{-1}$. The refractive index of the distilled water [12], PS [13] and PMMA [14] materials are calculated through a Sellmeier-type relation. The refractive index of the gold layer is calculated by the Drude model [15].

3. Results and discussions

We discuss the results for the effective indices, loss, spectral and amplitude sensitivities of a leaky core mode HE$_{11}$ in a hollow core Bragg optical fiber with or without a gold layer, for two assumed initial bandgap wavelengths ($\lambda_0 = 0.68 \mu m$ and $\lambda_0 = 0.5 \mu m$), when the dispersion of all layers is considered.

Figure 2 shows the real part of the effective index versus wavelength for the leaky core mode HE$_{11}$ near the lowest loss points: $\lambda = 0.4937 \mu m$ for $n_a$ and $\lambda = 0.4927 \mu m$ for $n_b$ + 0.001 for a structure without gold layer and $\lambda = 0.4932 \mu m$ for $n_a$ and $\lambda = 0.4922 \mu m$ for $n_b$ + 0.001 for an optical fiber with a gold layer when
Figure 2. The real part of the effective index versus wavelength for the leaky core mode HE$_{11}$ near the lowest loss points: $\lambda_0 = 0.4937$ $\mu$m for $n_a$ and $\lambda = 0.4927$ $\mu$m for $n_a + 0.001$ for a structure without gold layer (a) and $\lambda = 0.4932$ $\mu$m for $n_a$ and $\lambda = 0.4922$ $\mu$m for $n_a + 0.001$ for a structure with a gold layer (b) when $N = 11$. 

Figure 3. The loss spectra for the leaky core mode HE$_{11}$ near the lowest loss points: $\lambda = 0.4937$ $\mu$m for $n_a$, and $\lambda = 0.4927$ $\mu$m for $n_a + 0.001$ for a structure without gold layer (a) and $\lambda = 0.4932$ $\mu$m for $n_a$ and $\lambda = 0.4922$ $\mu$m for $n_a + 0.001$ for a structure with a gold layer (b).  

$\lambda_0 = 0.5$ $\mu$m. Figure 3 shows the loss spectra for the same mode near the same lowest loss points for a structure without and with a gold layer. For $t_g = d_H = 141.109$ 65 nm and $\lambda = 0.4932$ $\mu$m, the loss is about 3.27 times smaller in comparison with a structure without gold layer where $\lambda = 0.4937$ $\mu$m. Thus for a non-fundamental bandgap, the gold in the penultimate layer is a better reflector than a PS layer with the same thickness.

Figure 4 shows the loss spectra for the leaky core mode HE$_{11}$ near the lowest loss point $\lambda = 0.6678$ $\mu$m for $n_a$ and a structure without a gold layer when $\lambda_0 = 0.68$ $\mu$m. A similar figure is for $n_a + 0.001$ where $\lambda = 0.6663$ $\mu$m. Assuming that 0.1 nm spectral shift in the position of a bandgap center can be detected [10], the variation $\Delta \alpha$ of the losses is $2.562$ 788 $81 \times 10^{-10}$ dB cm$^{-1}$ when the wavelength $\lambda$ is changed from 0.6677 to 0.6678 $\mu$m. Also, $\Delta \alpha = 3.763$ 737 $42 \times 10^{-11}$ dB cm$^{-1}$ when $\lambda$ is changed from 0.6679 to 0.6678 $\mu$m. Figure 5 shows the loss spectra for the leaky core mode HE$_{11}$ near the lowest loss point $\lambda = 0.6506$ $\mu$m for $n_a$ and a structure with a gold layer when $\lambda_0 = 0.68$ $\mu$m. A similar figure is for $n_a + 0.001$ where $\lambda = 0.6493$ $\mu$m. For $t_g = d_H = 0.4937$ 6997 $\mu$m and $\lambda = 0.6506$ $\mu$m, the loss is about 11.68 times smaller in comparison with a structure without gold layer where $\lambda = 0.6678$ $\mu$m. Thus for a fundamental bandgap, the gold in the penultimate layer is a better reflector than a PS layer with the same thickness. Similarly, $\Delta \alpha = 2.138$ 632 $65 \times 10^{-11}$ dB cm$^{-1}$ when $\lambda$ is changed from 0.6505 to 0.6506 $\mu$m and $\Delta \alpha = 2.892$ 473 $39 \times 10^{-12}$ dB cm$^{-1}$ when $\lambda$ is changed from 0.6507 to 0.6506 $\mu$m.

Figure 6 shows the amplitude sensitivity for the leaky core mode HE$_{11}$ of a hollow core Bragg fiber with $N = 11$ layers versus wavelength near the lowest loss points ($\lambda = 0.4937$ $\mu$m, $S_A = 16.26$ RIU$^{-1}$ for a structure without gold layer and $\lambda = 0.4932$ $\mu$m, $S_A = 3.73$ RIU$^{-1}$ for a structure with a gold layer) when $\lambda_0 = 0.5$ $\mu$m. Figure 7 shows the amplitude sensitivity for the same mode versus wavelength near the lowest loss points.
(\lambda = 0.6678 \, \mu m, \, S_A = 19.86 \, \text{RIU}^{-1} \) for a structure without gold layer and \( \lambda = 0.6506 \, \mu m, \, S_A = 4.97 \, \text{RIU}^{-1} \) for a structure with a gold layer) when \( \lambda_0 = 0.68 \, \mu m \).

Figure 8 shows the loss versus the thickness \( t_g \) of the gold layer for the leaky core mode HE\(_{11} \) at the lowest loss point \( \lambda = 0.4932 \, \mu m \) when \( \lambda_0 = 0.5 \, \mu m \). For \( t_g = 28 \, \text{nm} \), the loss is about 272 times smaller in comparison with a structure without gold layer. Figure 9 shows the loss versus the thickness \( t_g \) of the gold layer for the same mode at the lowest loss point \( \lambda = 0.6506 \, \mu m \) when \( \lambda_0 = 0.68 \, \mu m \). Note that the optimized thickness \( t_g \) of the gold layer corresponds to change from positive (for small \( t_g \) as in the structure without a gold layer) to negative (for large \( t_g \)) in the imaginary part of the effective index.

Figure 10 shows the real part of the effective index versus wavelength for the leaky core mode HE\(_{11} \) near the lowest loss points: \( \lambda = 0.6503 \, \mu m \) for \( n_a \) and \( \lambda = 0.6502 \, \mu m \) for \( n_a + 0.001 \) for a structure with a gold layer when \( t_g = 41 \, \text{nm} \). The same figure shows the logarithmic in base 10 of the loss \( \alpha \) versus the wavelength. For an optimized structure (\( t_g = 28 \, \text{nm} \) and \( \lambda = 0.4942 \, \mu m \)), the loss is about 18 399 times smaller in comparison with a structure without a gold layer. The loss for the leaky core mode HE\(_{11} \) in the fundamental bandgap (\( \lambda_0 = 0.68 \, \mu m, \, t_g = 41 \, \text{nm} \)) is about 1186.2 times smaller than the non-fundamental bandgap (\( \lambda_0 = 0.5 \, \mu m, \, t_g = 28 \, \text{nm} \)).
Figure 12 shows the amplitude sensitivity for the leaky core mode HE_{11} of a hollow core Bragg fiber versus wavelength near the lowest loss points ($\lambda = 0.4937 \mu m, S_A = 16.26$ RIU$^{-1}$ for a structure without gold layer and $\lambda = 0.4932 \mu m, S_A = 3.73$ RIU$^{-1}$ for a structure with a gold layer).

Figure 13 shows the amplitude sensitivity for the same mode versus wavelength near the lowest loss points ($\lambda = 0.6678 \mu m, S_A = 19.86$ RIU$^{-1}$ for a structure without gold layer and $\lambda = 0.6506 \mu m, S_A = 4.97$ RIU$^{-1}$ for a structure with a gold layer) when $t_g = 197.6997$ nm.

Figure 6. The amplitude sensitivity for the leaky core mode HE_{11} of a hollow core Bragg fiber with $N = 11$ layers versus wavelength near the lowest loss points ($\lambda = 0.4937 \mu m, S_A = 16.26$ RIU$^{-1}$ for a structure without gold layer and $\lambda = 0.4932 \mu m, S_A = 3.73$ RIU$^{-1}$ for a structure with a gold layer).

Figure 7. The amplitude sensitivity for the leaky core mode HE_{11} of a hollow core Bragg fiber with $N = 11$ layers versus wavelength near the lowest loss points ($\lambda = 0.6678 \mu m, S_A = 19.86$ RIU$^{-1}$ for a structure without gold layer and $\lambda = 0.6506 \mu m, S_A = 4.97$ RIU$^{-1}$ for a structure with a gold layer) when $t_g = 197.6997$ nm.

Figure 12 shows the amplitude sensitivity for the leaky core mode HE_{11} of a hollow core Bragg fiber versus wavelength near the lowest loss points ($\lambda = 0.4942 \mu m, S_A = 9948.6$ RIU$^{-1}$) for a structure with a gold layer when $t_g = 28$ nm and $\lambda_0 = 0.5 \mu m$. Figure 13 shows the amplitude sensitivity for the same mode versus wavelength near the lowest loss points ($\lambda = 0.6505 \mu m, S_A = 1023.3$ RIU$^{-1}$) for a structure with a gold layer when $t_g = 41$ nm and $\lambda_0 = 0.68 \mu m$. The maximum value of the amplitude sensitivity ($S_A^{\max} = 2106.0$ RIU$^{-1}$ for $\lambda = 0.6504 \mu m$) for the leaky core mode HE_{11} in the fundamental bandgap ($\lambda_0 = 0.68 \mu m, t_g = 41$ nm) is about 4.7 times smaller than in the non-fundamental bandgap ($\lambda_0 = 0.5 \mu m, t_g = 28$ nm).

Tables 1 and 2 show the values of the effective index $b/k$, loss $\alpha$ and the lowest loss wavelength $\lambda$ for a hollow-core Bragg fiber with or without a gold layer when $\lambda_0 = 0.5 \mu m$ and $\lambda_0 = 0.68 \mu m$, respectively. The imaginary part of the effective index $\beta/k$ is very sensitive to the number of the layers and if the structure is with or without a gold layer. The values for the spectral and amplitude sensitivities for an optimized thickness ($t_g = 28$ nm for $\lambda_0 = 0.5 \mu m$ and $t_g = 41$ nm for $\lambda_0 = 0.68 \mu m$) of the gold layer can be determined from the tables 1 and 2 (modes 3 g, 3 g' and 3 g''). Tables 3 and 4 show the values of the shift $\delta \lambda_{\text{res}}$ towards lowest loss shorter wavelengths for an increase $\Delta n_a$ of the analyte refractive index by 0.001 RIU, the spectral sensitivity $S_\lambda$, the spectral resolution $\text{SR}_\lambda$, the amplitude sensitivity $S_A$ at the minimum-loss wavelength and the corresponding resolution $\text{SR}_A$, the transmission loss $\alpha$, the propagation length $L$ and the minimum-loss wavelength $\lambda$. Note
that the loss is decreased when the high index material just before the outermost region of a hollow core Bragg fiber is replaced by a gold layer.

The calculated spectral sensitivity \( S_\lambda = 1500 \) nm RIU\(^{-1}\) for a fiber without a gold layer is close to the theoretical value \( S_\lambda = 1634.67 \) nm RIU\(^{-1}\) for the HE\(_{11}\) mode when \( \lambda_0 = 0.68 \) \( \mu \)m. Also, the calculated spectral sensitivity \( S_\lambda = 1000 \) nm RIU\(^{-1}\) for a fiber without a gold layer is close to the theoretical value \( S_\lambda = 1166.98 \) nm RIU\(^{-1}\) for the HE\(_{11}\) mode when \( \lambda_0 = 0.5 \) \( \mu \)m. Note that this sensitivity is smaller than in the fundamental bandgap \( \lambda_0 = 0.68 \) \( \mu \)m.

The theoretical value \( S_\lambda = 2475.97 \) nm RIU\(^{-1}\) of the spectral sensitivity for the HE\(_{11}\) mode of a hollow-core Bragg fiber \( \lambda_0 = 0.5 \) \( \mu \)m, \( r_c = 25.0 \) \( \mu \)m, \( n_1 = 1.34, n_{H1} = 1.6, n_1 = 1.4, d_H = 0.142 971 57 \mu m, d_L = 0.308 289 76 \mu m [5] \) without a gold layer is smaller in comparison with \( S_\lambda = 5300 \) nm RIU\(^{-1}\) computed in \([10]\) for the same values of \( r_c, n_1, n_{H1}, n_L \) and \( \lambda_0 \).

4. Conclusions

An analytical method is used to determine the propagation characteristics for HE\(_{11}\) mode in a hollow core Bragg fiber with or without a gold layer for two assumed initial bandgap wavelengths \( \lambda_0 = 0.68 \) \( \mu \)m and \( \lambda_0 = 0.5 \) \( \mu \)m when the dispersion relations for all layers (water, PS, PMMA and gold) are considered.
Figure 10. (a) The real part of the effective index versus wavelength for the leaky core mode HE$_{11}$ near the lowest loss points:
\[ \lambda = 0.4942 \ \mu m \text{ for } n_a \text{ and } \lambda = 0.4940 \ \mu m \text{ for } n_a + 0.001 \text{ for a structure with a gold layer when } t_g = 28 \ \text{nm} \text{ and } N = 11. \] (b) The logarithmic in base 10 of the loss \( \alpha \) versus the wavelength for the same structure.

Figure 11. (a) The real part of the effective index versus wavelength for the leaky core mode HE$_{11}$ near the lowest loss points:
\[ \lambda = 0.6503 \ \mu m \text{ for } n_a \text{ and } \lambda = 0.6502 \ \mu m \text{ for } n_a + 0.001 \text{ for a structure with a gold layer when } t_g = 41 \ \text{nm} \text{ and } N = 11. \] (b) The logarithmic in base 10 of the loss \( \alpha \) versus the wavelength for the same structure.

Figure 12. The amplitude sensitivity for the leaky core mode HE$_{11}$ of a hollow core Bragg fiber with \( N = 11 \) layers versus wavelength near the lowest loss points (\( \lambda = 0.4942 \ \mu m, S_A = S_A^{m} = 9948.6 \text{ RIU}^{-1} \)) for a structure with a gold layer when \( t_g = 28 \ \text{nm} \).
Figure 13. The amplitude sensitivity for the leaky core mode $HE_{11}$ of a hollow core Bragg fiber with $N = 11$ layers versus wavelength near the lowest loss points ($\lambda = 0.6503 \, \mu m$, $S_0 = 1023.3 \, RIU^{-1}$) for a structure with a gold layer when $t_g = 41 \, nm$. The maximum value $S_\text{max} = 2106.0 \, RIU^{-1}$ of the amplitude sensitivity is at $\lambda = 0.6504 \, \mu m$.

Table 1. Values of the effective index $\beta/k$, loss $\alpha$ and wavelength $\lambda$ for a hollow-core Bragg fiber with $N = 11$ layers, $t_1 = 25.0 \, \mu m$, $d_1 = 0.141 \, 109 \, 65 \, \mu m$, $d_2 = 0.186 \, 191 \, 94 \, \mu m$, $n_1 = n_{RI1}$, $n_2 = n_3 = \ldots = n_{10} = n_{P3G}$, $n_4 = n_5 = \ldots = n_{11} = n_{P3MA}$ for a fiber without a gold layer and $n_l = n_{RI1}$, $n_2 = n_3 = \ldots = n_{10} = n_{P3G}$, $n_4 = n_5 = \ldots = n_{11} = n_{P3MA}$ for a fiber with a gold layer.

| Mode; $\lambda$; $n_1$; $t_g$; $\beta/k$ | $\alpha$ (dB cm$^{-1}$) | $\lambda$ (\mu m) |
|-------------------------------------|------------------------|------------------|
| 1; 0.5; 5; $n_1$; 1; 0.5; 0.001; 1 | 1.336 624 17 + 3.812 711 17 $\times 10^{-1}$ | 4.214 683 39 $\times 10^{-2}$ | 0.4937 |
| 2 g; 0.5; $n_1$; $d_1$ | 1.336 674 60 + 3.741 528 16 $\times 10^{-1}$ | 4.144 390 14 $\times 10^{-2}$ | 0.4927 |
| 2 g; 0.5; $n_1$; $d_1$; $d_1$ | 1.336 699 90 - 1.136 588 96 $\times 10^{-1}$ | 1.282 423 92 $\times 10^{-2}$ | 0.4922 |
| 3 g; 0.5; $n_1$; 28 | 1.336 699 06 - 2.074 331 85 $\times 10^{-12}$ | 2.290 707 67 $\times 10^{-8}$ | 0.4942 |
| 3 g; 0.5; $n_1$; 0.001; 28 | 1.337 599 07 - 2.271 101 12 $\times 10^{-12}$ | 2.508 002 15 $\times 10^{-8}$ | 0.4942 |
| 3 g; 0.5; $n_1$; 0.001; 28 | 1.337 609 10 - 4.775 333 68 $\times 10^{-12}$ | 5.276 030 85 $\times 10^{-8}$ | 0.4940 |

Table 2. Values of the effective index $\beta/k$, loss $\alpha$ and wavelength $\lambda$ for a hollow-core Bragg fiber with $N = 11$ layers, $t_1 = 25.0 \, \mu m$, $d_1 = 0.197 \, 699 70 \, \mu m$, $d_2 = 0.255 \, 639 47 \, \mu m$, $n_1 = n_{RI1}$, $n_2 = n_3 = \ldots = n_{10} = n_{P3G}$, $n_4 = n_5 = \ldots = n_{11} = n_{P3MA}$ for a fiber without a gold layer and $n_1 = n_{RI1}$, $n_2 = n_3 = \ldots = n_{10} = n_{P3G}$, $n_4 = n_5 = \ldots = n_{11} = n_{P3MA}$ for a fiber with a gold layer.

| Mode; $\lambda$; $n_1$; $t_g$; $\beta/k$ | $\alpha$ (dB cm$^{-1}$) | $\lambda$ (\mu m) |
|-------------------------------------|------------------------|------------------|
| 1; 0.68; 5; $n_1$; 1; 0.68; 0.001; 1 | 1.337 729 94 + 7.842 549 73 $\times 10^{-1}$ | 6.409 217 98 $\times 10^{-3}$ | 0.6678 |
| 2 g; 0.68; $n_1$; $d_1$ | 1.337 765 69 + 7.665 612 89 $\times 10^{-11}$ | 6.278 721 87 $\times 10^{-11}$ | 0.6663 |
| 2 g; 0.68; $n_1$; $d_1$; $d_1$ | 1.338 149 98 - 6.539 394 79 $\times 10^{-12}$ | 5.485 518 37 $\times 10^{-12}$ | 0.6506 |
| 3 g; 0.68; $n_1$; 41 | 1.338 182 68 - 6.489 222 61 $\times 10^{-12}$ | 5.454 330 44 $\times 10^{-6}$ | 0.6493 |
| 3 g; 0.68; $n_1$; 0.001; 41 | 1.338 157 48 - 2.301 183 45 $\times 10^{-15}$ | 1.931 219 61 $\times 10^{-9}$ | 0.6503 |
| 3 g; 0.68; $n_1$; 0.001; 41 | 1.338 159 98 - 1.074 670 25 $\times 10^{-15}$ | 9.020 330 25 $\times 10^{-15}$ | 0.6502 |

Table 3. Values of $\delta \lambda_{	ext{res}}$ (nm), $S_0$ (nm RIU$^{-1}$), $S_\text{R}$ (RIU), $S_\text{A}$ (RIU), $\alpha$ (dB cm$^{-1}$), $L$ (\mu m) and $\lambda$ (\mu m) where $r_g$ is the radius of the core, $N$ is the number of layers, $n_1$ is the high refractive index, $n_0$ is the low refractive index and $n_12$ is the refractive index of the analyte.

| Mode $HE_{11}$; $\lambda$ (\mu m); $r_g$; $N$; $n_1$; $n_0$; $n_2$; $n_{N-1}$; $n_{N}$ | $\delta \lambda_{\text{res}}$ | $S_0$ | $S_\text{R}$ | $S_\text{A}$ | $\alpha L$ | $\lambda$ |
|-------------------------------------|------------------------|--------|--------|--------|-----------|--------|
| 1; 0.5 | 1.0 | 1000 | 16.3 | 4.2 $\times 10^{-2}$ | 0.4937 |
| 2 g; 0.5; $t_g$ = $d_1$ | 1.0 | 1000 | 3.7 | 1.3 $\times 10^{-2}$ | 0.4932 |
| 3 g; 0.5; $t_g$ = 28 nm | 0.2 | 200 | 9948.6 | 2.3 $\times 10^{-6}$ | 0.4942 |
When a high index material just before the outermost region of a hollow core Bragg fiber is replaced by a gold layer with an optimized thickness, the optical confinement at the minimum-loss wavelength for the HE11 mode in the core is increased about 33 187.4 times for \( \lambda_0 = 0.68 \, \mu \text{m} (t_\varnothing = 41 \, \text{nm}) \) and about 18 399 times for \( \lambda_0 = 0.5 \, \mu \text{m} (t_\varnothing = 28 \, \text{nm}) \) for \( N = 11 \) layers. Also, the amplitude sensitivity \( S_A \) at the minimum-loss wavelength is increased from \( S_A = 16.3 \, \text{RIU}^{-1} (\lambda = 0.4937 \, \mu \text{m}) \) to \( S_A = 9948.6 \, \text{RIU}^{-1} (\lambda = 0.4942 \, \mu \text{m}) \) for \( \lambda_0 = 0.5 \, \mu \text{m} \) and from \( S_A = 19.9 \, \text{RIU}^{-1} (\lambda = 0.6678 \, \mu \text{m}) \) to \( S_A = 1023.3 \, \text{RIU}^{-1} (\lambda = 0.6503 \, \mu \text{m}) \) for \( \lambda_0 = 0.68 \, \mu \text{m} \). However, the spectral sensitivity is smaller when a gold layer is used in the place of a PS layer.

The optical confinement for the HE11 mode in the water-filled core for a fundamental and also for a nonfundamental bandgap wavelength is increased over four orders (10^4) of magnitude when a high index material just before the outermost region of a hollow core Bragg fiber is replaced by a gold layer with an optimized thickness. Thus an optimized thin gold layer is a better reflector than a thick PS layer. In such devices, the light of a high power laser can be transmitted with very low loss due to the large confinement in the core of the fiber.

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### Table 4. Values of \( \delta \lambda_{\text{res}} \) (nm), \( S_A \) (RIU), \( \Delta \alpha (\text{dB cm}^{-1}) \), \( L(\mu \text{m}) \) and \( \lambda(\mu \text{m}) \) where \( r_\varnothing \) is the radius of the core, \( N \) is the number of layers, \( n_1 \) is the high refractive index, \( n_2 \) is the low refractive index and \( n_4 \) is the refractive index of the analyte.

| Mode HE11, \( \lambda_0(\mu \text{m}) \); \( n_1; n_0; n_2; n_4; n_{N-1} \) | \( \delta \lambda_{\text{res}} \) | \( S_A \) | \( S_A \) | \( \Delta \alpha L \) | \( \lambda \) |
|---|---|---|---|---|---|
| 1:0.68; \( n_1; n_0; n_2; n_4; n_{N-1} \) | 1.5 | 1500 | 19.9 | 6.4 \times 10^{-5} | 0.6678 |
| 2 g:0.68; \( t_\varnothing = d_1 \) | 1.3 | 1300 | 4.97 | 5.5 \times 10^{-6} | 0.6506 |
| (25; 11): \( n_1; n_0; n_2; n_4; n_9 \) | 7.7 \times 10^{-5} | 2.0 \times 10^{-3} | 1.9 \times 10^{-9} |
| (25; 11): \( n_1; n_0; n_2; n_4; n_9 \) | 1.0 \times 10^{-3} | 9.8 \times 10^{-6} | 5.3 \times 10^{-5} | 0.6503 |