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SPECTRAL AND AMPLITUDE SENSITIVITIES OF THE HE_{11} MODE IN A HOLLOW-CORE BRAGG FIBER WITH A GOLD LAYER

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Abstract. The spectral and amplitude sensitivities of the HE_{11} mode in a hollow-core Bragg fiber with or without gold layer are investigated by using an analytical method. This method is applied for different structures without or with a gold layer made from 11, 9, 8, and 5 layers. The amplitude sensitivity at the minimum-loss wavelength increases when the number N of the layers increases from $N = 5$ to $N = 11$. When a high index material just before the outermost region of a hollow-core Bragg fiber is replaced by a gold layer, the optical confinement for the HE_{11} mode in the core increases about two times.

Key words: sensors, hollow core fibers, Bragg fiber, metal coating, photonic band gap.

1. INTRODUCTION

The transfer matrix method has been used for the analysis of planar waveguides [1], optical fibers [2–5], fiber gratings [6, 7], fiber based plasmonic sensors [8–11], and hollow core Bragg fiber [12].

In recently-published papers [8–10], a transfer matrix method was applied to an optical fiber with four (or five) layers made by SiO_2 core surrounded by a GaP layer, a gold layer and by a water layer, which can be considered infinite for the numerical model. In this case, the radial solutions of the Maxwell equations are written as a combination of Bessel functions of the first kind (J) in the core layer, Bessel functions of the first and second kinds (J and Y) in the dielectric interior clad layers, a linear combination of the Hankel functions H_1 and H_2 in the gold region just before the outermost sensing region, and modified Bessel function of the second kind (K) in the outermost region.

In a very recent paper [12] a new transfer matrix method is applied to a hollow-core Bragg fiber with a gold layer. In this method, the radial solutions of the Maxwell equations are represented by a Bessel function of the first kind (J) in the core region, a linear combination of Bessel functions of the first and second kinds (J and Y) in the dielectric interior layers, a linear combination of the Hankel functions (H_1 and H_2) in the gold region, and a Hankel function of the first kind H_1 in the external infinite medium. When a high index material just before the outermost region of a hollow core Bragg fiber ($r_c = r_1 = 13.02$ µm, $n_c = n_1 = 1$, $d_H = 0.086303$ µm, $d_L = 0.310248$ µm, $n_2 = n_4 = ... = n_{N-3} = 4.6$, $n_{N-1} = n_{gold}$, $n_3 = n_5 ... = n_N = 1.6$), 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 increases about ten times. Our method is in good agreement with the data known from the literature in the case of a hollow-core Bragg fiber without a gold layer. Thus for a hollow-core Bragg fiber with $N = 34$ layers (32 reflector layers, 16 pairs), $r_c = 1.3278$ µm, $n_c = n_1 = 1$, $d_H = 0.2133$ µm, $d_L = 0.346$ µm, $n_2 = n_4 = ... = n_{34} = 1.49$, $n_3 = n_5 ... = n_{33} = 1.17$, $\lambda = 1$ µm, our effective index for the TE_{01} mode $\beta/k = 0.8910672175 + 1.4226046712\times10^{-8}i$ is very close to the calculated value in Ref. [13], $\beta/k = 0.891067 + 1.4226\ 10^{-8}$ i.

In this paper we extend the research to the HE_{11} mode and our transfer matrix method is applied to a hollow-core Bragg optical fiber with a relatively small index contrast between the refractive indices n_H and n_L in the cladding region and the refractive index of the core is larger than 1. The optical confinement for the HE_{11} mode in the core increases about two times when the high index material just before the outermost region of a hollow-core Bragg fiber is replaced by a gold layer.

2. HOLLOW-CORE BRAGG FIBER WITHOUT AND WITH A GOLD LAYER

For a hollow-core Bragg fiber (see Fig. 1) with five layers (N = 5) and without a gold layer, the fiber parameters are r_c =25.0 µm, d_H = 0.14297157 µm, d_L = 0.30828976 µm, n_1 = 1.34, n_2 = n_4 = n_H= 1.6, n_3 = n_5= = n_L = 1.4. If we replace the fourth dielectric layer with a gold layer, then n_4 = n_g= 0.578555 – 2.190515i for λ = 0.5321 µm (the wavelength of lowest propagation loss for the HE_{11} two-fold degenerate mode). In general, when N is odd (N = 5, 9, 11), n_1 = 1.34, n_2 = n_4 = ... n_{N-1} = n_H= 1.6, n_3 = n_5 = ...= n_N = n_L = 1.4 for a fiber without a gold layer and n_1 = 1.34, n_2 = n_4 = ... n_{N-3} = n_H= 1.6, n_3 = n_5 = ...= n_N = 1.4 and n_{N-1} = n_g for a fiber with a gold layer. When N is even (N = 8), n_1 = 1.34, n_2 = n_4 = ... n_N = 1.6, n_3 = n_5 = ...= n_{N-1} = 1.4 for a fiber without a gold layer and n_1 = 1.34, n_2 = n_4 = ... n_N = 1.6, n_3 = n_5 = ...= n_{N-3} = 1.4 and n_{N-1} = n_g for a fiber with a gold layer.

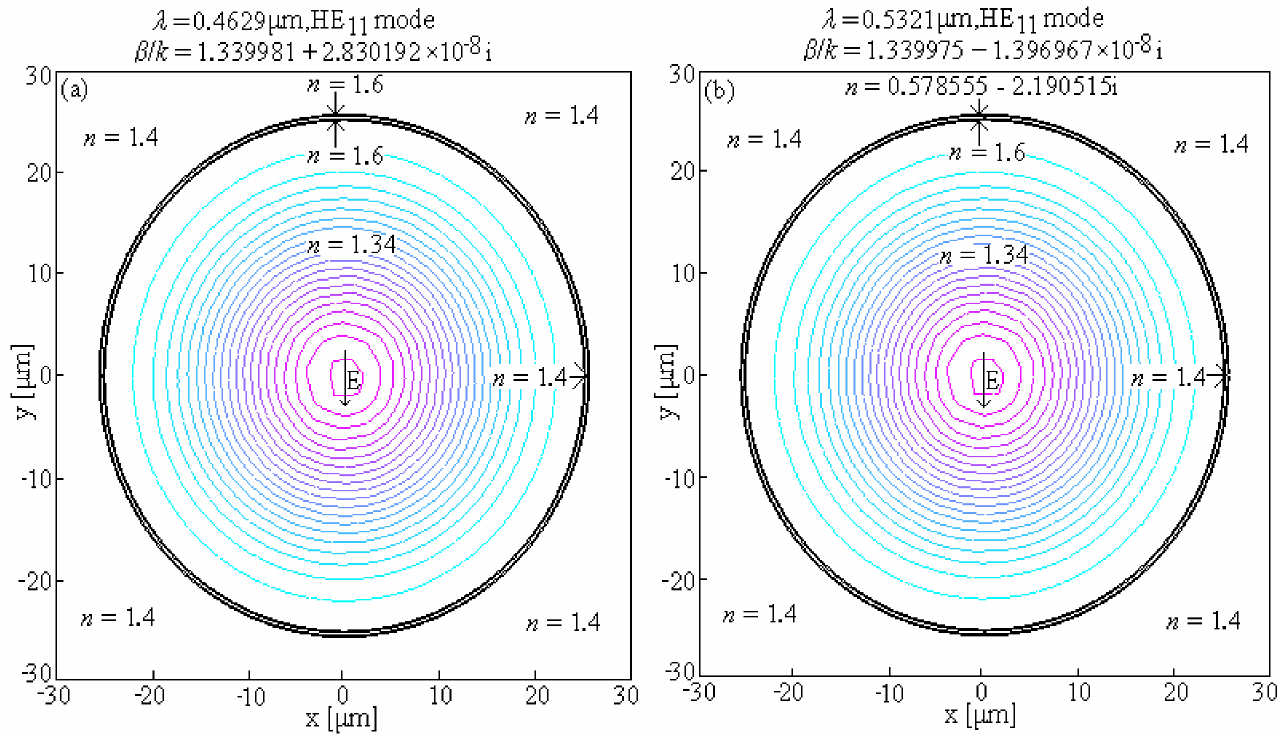

Fig. 1 – A cross section of a hollow-core Bragg fiber with five layers (N = 5) and a contour plot of the z-component of the Poynting vector at λ = 0.4629 µm for n_4 = 1.6 (a) and at λ = 0.5321 µm when n_4 = 0.578555 – 2.190515i (b) of the fiber lowest loss for the HE_{11} two-fold degenerate mode. The arrow shows the orientation of the main electric field E.

The thicknesses d_H and d_L are determined by using the usual quarter wave condition [14]:

$$d_H = \frac{\lambda_0}{4\sqrt{n_H^2 - n_c^2}}, \; d_L = \frac{\lambda_0}{4\sqrt{n_L^2 - n_c^2}}. \tag{1}$$

where λ_0 = 0.5 µm is the wavelength of assumed initial bandgap.

The theoretical spectral sensitivity S_λ [15]

$$S_\lambda = 2n_c\left(\frac{d_H}{\sqrt{n_H^2 - n_c^2}} + \frac{d_L}{\sqrt{n_L^2 - n_c^2}}\right) \tag{2}$$

increases for high values of the refractive index n_c = n_1 = n_a of the analyte. In our example, d_H= 142.972 nm, d_L = 308.290 nm, and S_λ = 2476 nm/RIU.

For the same wavelength, the real parts of the effective indices β / k for the hollow-core Bragg fiber with or without gold layer are the same and for large number of layers can be approximated with the theoretical value given by the relation [16]:

$$\mathrm{Re}(\beta/k)_T \approx \sqrt{n_c^2 - \left(\frac{J_1^{'}\lambda}{2\pi r_c}\right)^2} \tag{3}$$

where $J_1^{'}$ = 1.84118378134065 is the first root of the derivative of Bessel function $J_1(x)$. For λ = 0.4866 µm, $\mathrm{Re}(\beta/k)_T$ = 1.33998786 is close to the simulated value $\mathrm{Re}(\beta/k)$ = 1.33997931 (Table 1) when N = 8. The refractive index of the gold layer is calculated by the Drude model [17].

3. NUMERICAL RESULTS AND DISCUSSION

Figure 1 shows a cross section of a hollow-core Bragg fiber with five layers (N = 5) and a contour plot of the z-component $S_z(x, y)$ of the Poynting vector at λ = 0.4629 µm for n_4 = 1.6 and at λ = 0.5321 µm when n_4 = 0.578555 – 2.190515i of the fiber lowest loss for the HE_{11} two-fold degenerate mode.

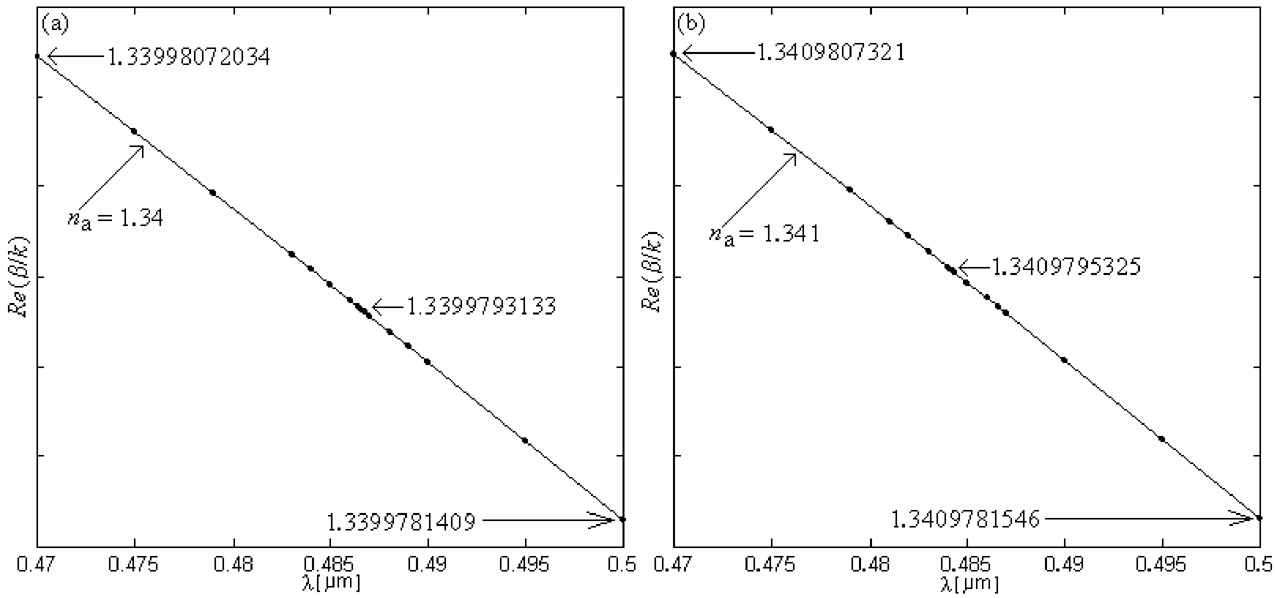

Fig. 2 – The real part of the effective index *versus* wavelength for the leaky core mode HE_{11} near the lowest loss point (λ = 0.4866 µm) for n_a = 1.34 (a) and near the lowest loss point (λ = 0.4842 µm) for n_a = 1.341 (b) for a hollow-core Bragg fiber with N = 8 layers.

Table 1 shows the values of the effective index β/k, loss α and wavelength λ for a hollow-core Bragg fiber with 5, 8, 9, and 11 layers. The real part of the effective index shows a slow decrease (Fig. 2) with the wavelength for the leaky core mode HE_{11} near the lowest loss point (λ = 0.4866 µm) for n_a = 1.34 and near the lowest loss point (λ = 0.4842 µm) for n_a = 1.341 for a hollow-core Bragg fiber with N = 8 layers. The imaginary part of the effective index β/k is very sensitive to the number of the layers and if the structure is with or without a gold layer.

The minimum-loss wavelength λ_{min} and the corresponding propagation length shift toward a short wavelength (Fig. 3) as the refractive index of the core layer n_c increases from n_a = 1.34 to n_a = 1.341. The spectral sensitivity (S_λ = 2400 nm/RIU) for a fiber with N = 8 layers is very close to the theoretical value (S_λ = 2475.97 nm/RIU) for the HE_{11} mode, in contradiction with the published value [14] for a similar fiber structure where S_λ = 5300 nm/RIU.

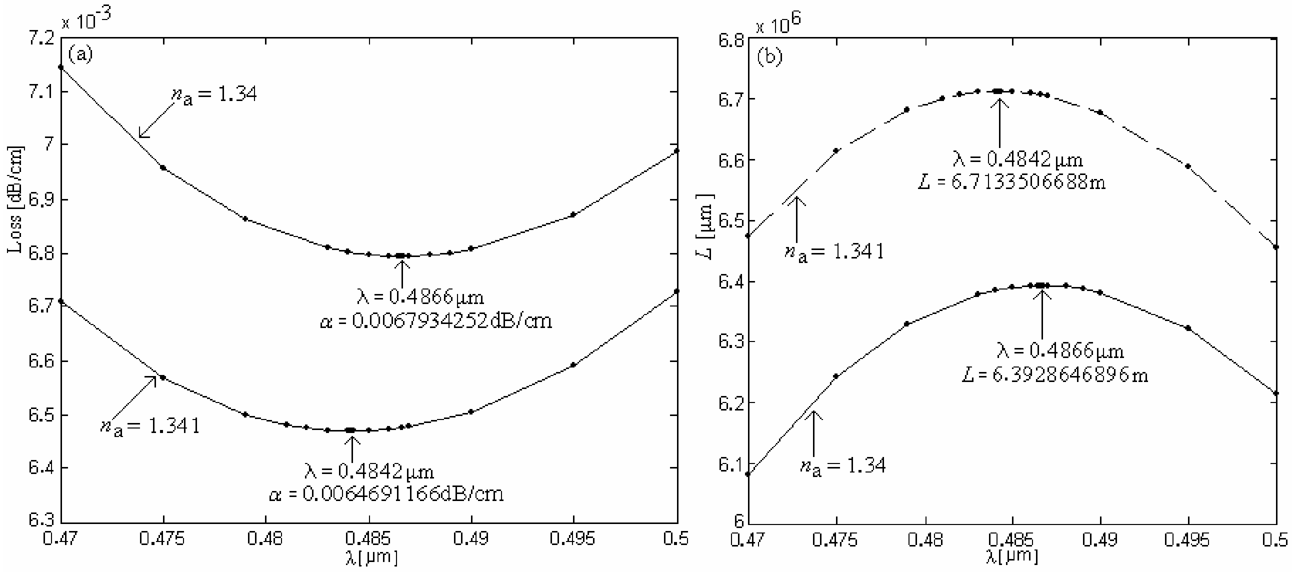

Fig. 3 – The loss spectra (a) and propagation length (b) for the leaky core mode HE_{11} near the lowest loss point (λ = 0.4866 μm) for n_a = 1.34 and near the lowest loss point (λ = 0.4842 μm) for n_a = 1.341 for a hollow-core Bragg fiber with N = 8 layers.

Table 1

Values of the effective index β / k, loss α, and wavelength λ for a hollow-core Bragg fiber with 5, 8, 9, and 11 layers

Mode; n_1	β / k	α [dB/cm]	λ[μm]
1;N = 5;1.34	1.33998130 + 2.83019228×10^{-8} i	3.33674437×10^{-2}	0.4629
1';N = 5;1.341	1.34098146 + 2.74122775×10^{-8} i	3.24517685×10^{-2}	0.4610
2g;N = 5;1.34	1.33997518 - 1.396966851×10^{-8} i	1.43280477×10^{-2}	0.5321
2g';N = 5;1.341	1.34097530 - 1.391769821×10^{-8} i	1.43043151×10^{-2}	0.5310
3;N = 8;1.34	1.33997931 + 6.05712768×10^{-9} i	6.79342522×10^{-3}	0.4866
3';N = 8;1.341	1.34097953 + 5.73952019×10^{-9} i	6.46911659×10^{-3}	0.4842
4g;N = 8;1.34	1.33997661 - 1.26375622×10^{-8} i	1.33403413×10^{-2}	0.5170
4g';N = 8;1.341	1.34097678 - 1.25029560×10^{-8} i	1.32417912×10^{-2}	0.5153
5;N = 9;1.34	1.33997909 + 3.60227051×10^{-9} i	4.01868578×10^{-3}	0.4892
5';N = 9;1.341	1.34097930 + 3.39312369×10^{-9} i	3.80324316×10^{-3}	0.4869
6g;N = 9;1.34	1.33997766 - 1.75192309×10^{-9} i	1.89179457×10^{-3}	0.5054
6g';N = 9;1.341	1.34097785 - 1.70502101×10^{-9} i	1.84846274×10^{-3}	0.5034
7;N = 11;1.34	1.33997881 + 1.28543289×10^{-9} i	1.42470694×10^{-3}	0.4924
7';N = 11;1.341	1.34097903 + 1.19481749×10^{-9} i	1.33075978×10^{-3}	0.4900
8g;N = 11;1.34	1.33997785 - 6.29559007×10^{-10} i	6.82658790×10^{-4}	0.5033
8g';N = 11;1.341	1.34097806 - 6.04755772×10^{-10} i	6.58642466×10^{-4}	0.5011

Figure 4 shows the amplitude sensitivity for the leaky core mode HE_{11} of a hollow core Bragg fiber with N = 8 layers versus wavelength near the lowest loss point (λ = 0.4866 μm). The amplitude sensitivity at the minimum-loss wavelength is S_A = 46.82 RIU^{-1}, which is comparable with the calculated value in [14] at the same wavelength.

Figue 5 shows the loss spectra for the leaky core mode HE_{11} near the lowest loss points for a hollow-core fiber without and with a gold layer for two values of N (N = 9 and N = 11) and for two values of the refractive index of the analyte (n_a = n_c = 1.34 and n_a = 1.341). Note that the loss is decreasing with the increase of N and n_a, and also when the high index material just before the outermost region of the hollow-core Bragg fiber is replaced by a gold layer.

The amplitude sensitivity for the leaky core mode HE_{11} near the lowest loss point for the hollow-core Brag fiber without and with a gold layer increases when the number of the layers increases from N = 5 to N = 11 (Fig. 6).

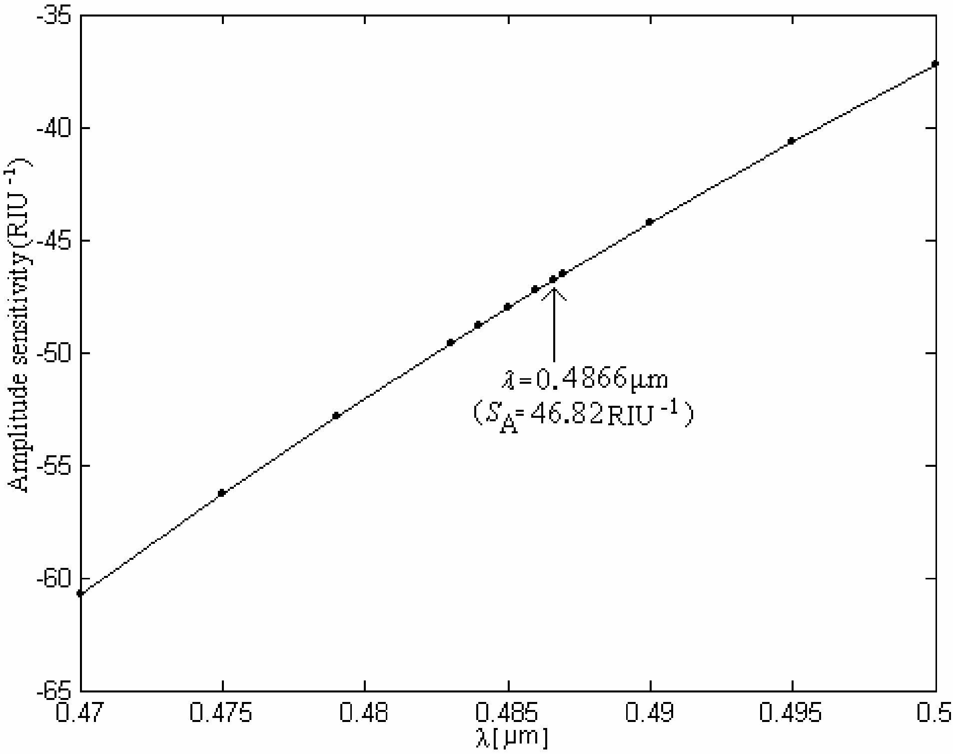

Fig. 4 – The amplitude sensitivity for the leaky-core mode HE_{11} of a hollow-core Bragg fiber with $N = 8$ layers *versus* wavelength near the lowest loss point ($\lambda = 0.4866$ µm) where the amplitude sensitivity is $S_A = 46.82$ RIU^{-1}.

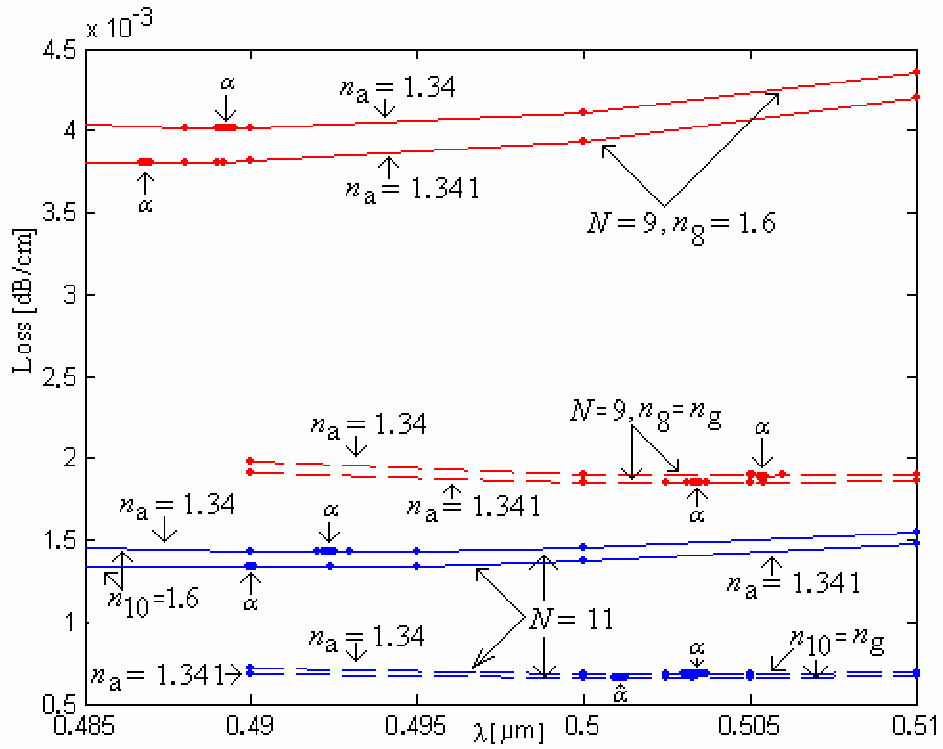

Fig. 5 – The loss spectra for the leaky core mode HE_{11} near the lowest loss points ($\lambda = 0.4892$ µm, $N = 9$, $n_a = 1.34$, $n_8 = 1.6$), ($\lambda = 0.4869$ µm, $N = 9$, $n_a = 1.341$, $n_8 = 1.6$), ($\lambda = 0.5054$ µm, $N = 9$, $n_a = 1.34$, $n_8 = n_g$), ($\lambda = 0.5034$ µm, $N = 9$, $n_a = 1.341$, $n_8 = n_g$), ($\lambda = 0.4924$ µm, $N = 11$, $n_a = 1.34$, $n_{10} = 1.6$), ($\lambda = 0.4900$ µm, $N = 9$, $n_a = 1.341$, $n_{10} = 1.6$), ($\lambda = 0.5033$ µm, $N = 11$, $n_a = 1.34$, $n_{10} = n_g$), ($\lambda = 0.5011$ µm, $N = 9$, $n_a = 1.341$, $n_{10} = n_g$).

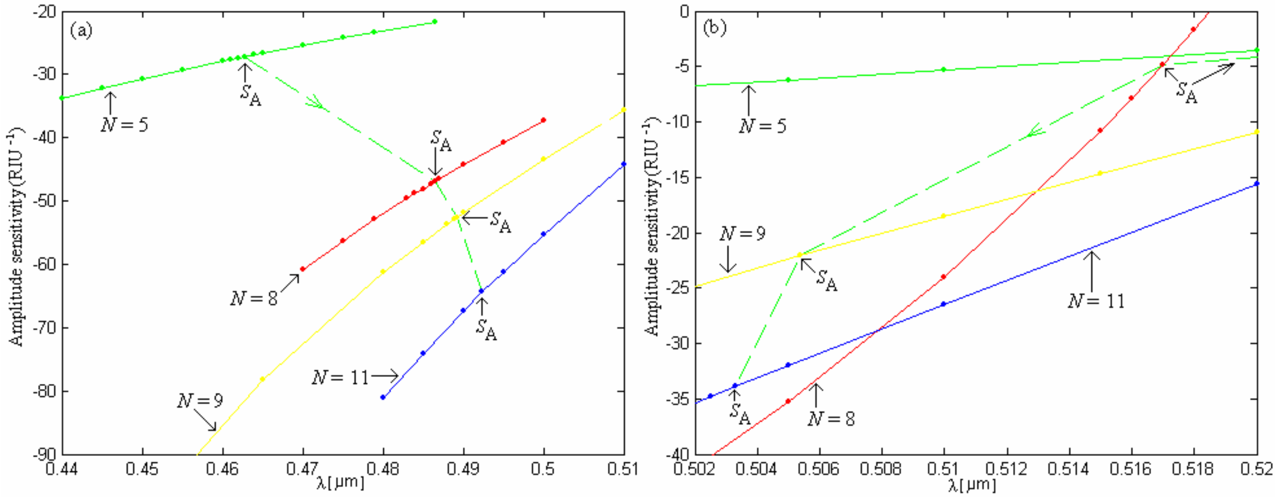

Fig. 6 – The amplitude sensitivity for the leaky core mode HE_{11} versus wavelength near the lowest loss point for a hollow- core Brag fiber without (a) and with (b) a gold layer. The arrow shows the increase of the amplitude sensitivity at the minimum-loss wavelength when the number of the layers is increased from $N = 5$ to $N = 11$.

Table 2 shows the values of the shift $\delta\lambda_{res}$ towards longer wavelengths of the phase matching point or loss matching point for an increase Δn_a of the analyte refractive index by 0.001 RIU, the spectral sensitivity S_λ, the spectral resolution SR_λ, the amplitude sensitivity S_A at the minimum-loss wavelength and the corresponding resolution SR_A, the transmission loss α, the propagation length L, and the minimum-loss wavelength λ.

Table 2

Values of $\delta\lambda_{res}$ [nm], S_λ [nmRIU^{-1}], SR_λ [RIU], S_A [RIU^{-1}], SR_A [RIU], α [dB/cm], L [μm], and λ [μm]

Mode HE_{11} (r_c;N; n_H; n_L; n_a;n_{N-1};n_N)	$\delta\lambda_{res}$	S_λ SR_λ	S_A SR_A	α L	λ
1 (25;5;1.6;1.4;1.34;1.6; 1.4)	1.9	1900 5.3×10^{-5}	27.2 3.7×10^{-4}	3.3×10^{-2} 1.3×10^{6}	0.4629
2g (25;5;1.6;1.4;1.34;n_g; 1.4)	1.1	1100 9.1×10^{-5}	1.6 6.4×10^{-3}	1.4×10^{-2} 3.0×10^{6}	0.5321
3 (25;8;1.6;1.4;1.34; 1.4;1.6)	2.4	2400 4.2×10^{-5}	46.8 2.1×10^{-4}	6.8×10^{-3} 6.4×10^{6}	0.4866
4g (25;8;1.6;1.4;1.34; n_g; 1.6)	1.7	1700 5.9×10^{-5}	4.8 2.1×10^{-3}	1.3×10^{-2} 3.3×10^{6}	0.5170
5 (25;9;1.6;1.4;1.34; 1.6; 1.4)	2.3	2300 4.3×10^{-5}	52.6 1.9×10^{-4}	4.0×10^{-3} 1.1×10^{7}	0.4892
6g (25;9;1.6;1.4;1.34; n_g; 1.4)	2.0	2000 5.0×10^{-5}	22.1 4.5×10^{-4}	1.9×10^{-3} 2.3×10^{7}	0.5054
7 (25;11;1.6;1.4;1.34;1.6; 1.4)	2.4	2400 4.2×10^{-5}	64.4 1.6×10^{-4}	1.4×10^{-3} 3.0×10^{7}	0.4924
8g (25;11;1.6;1.4;1.34;n_g; 1.4)	2.2	2200 4.5×10^{-5}	33.9 2.9×10^{-4}	6.8×10^{-4} 6.4×10^{7}	0.5033

4. CONCLUSIONS

The spectral sensitivity (S_λ = 2 400 nm/RIU) for a fiber without a gold layer with N = 8 layers is very close to the theoretical value (S_λ = 2 475.97 nm/RIU) for the HE_{11} mode, in contradiction with the published value [14] for a similar fiber structure where S_λ = 5 300 nm/RIU. When a high index material just before the outermost region of a hollow-core Bragg fiber is replaced by a gold layer, the optical confinement for the HE_{11} mode in the core is increased about two times for any number of layers, namely 2.33 for $N = 5$, 2.12 for $N = 9$, and 2.09 for $N = 11$. As in the case of TE_{01} mode [12], 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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