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Research Article

SPR Aided PCF based Beam Modifiers for Efficient Coupling to Rectangular Planar Waveguides

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Abstract

This work explores the possibility of fluid /Polymer/metal infiltration based guidance control for 3D mode transformers. Elliptical beam profiles have been realized using SPR effect and selective fluid infiltration in tapered micro structures (LMAPCF). Possibility of achieving required mode aspect ratio (1:3) has been demonstrated through simulation. Programmable beam profile modifications can be achieved through RI tuning of the infiltrates.

Keywords: *Fluid infiltrated PCF, Tapered Micro structured Fiber; Surface Plasma Resonance (SPR), Ellipticity.*

1. Introduction

Three dimensional (3D) optical beam modifiers are essential to convert input circular beam from a standard 9μm single mode fiber (SMF) to an elliptical beams that couple to the modes of rectangular silicon waveguides of dimensions of the order of hundreds of nm in all silicon photonics applications. The high refractive index of silicon makes it necessary to reduce the dimensions to this order in order to ensure single mode propagation. Apart from this, the Fresnel reflection losses at the air/silicon interfaces should also be reduced to ensure good coupling. In case of coupling from sources to planar silicon waveguides, the requirement is for structures which can couple from large mode area to the elliptical modes of silicon waveguides. Zhou *et al* (2012) has shown aspect ratios of 5:1 in large mode area (LMA) fibers through tapering of LMA after a selective collapse of holes to modify the circular core to a rectangular/elliptical core. Instead of selective collapsing if selective infiltration is done to effect the same beam transformation and the index of the infiltrate (Electro-optical polymer) can be reconfigured through electro-optic effects, then one can realize programmable beam modifications and dispersion characteristics.

Surface plasma resonance (SPR) is a prominent optical phenomenon, which involves resonant excitation of collective oscillations of free electrons in metal by electromagnetic surface waves. Surface plasmons induced at the metal/dielectric interface, are extremely sensitive to changes in the RI of the dielectric. Surface plasmons can be excited by light when the phase matching condition is met between the exciting light and the surface plasmons which will generate a loss peak. The metal layer acts like a reflector for electromagnetic waves with frequencies lesser than plasmonic resonance frequency ω_p of the metal where the real part of the dielectric constant is negative. This has been exploited to realize highly sensitive PCF based SPR sensors (Ahmmed *et al* 2015, Pone *et al* 2008 &Hassani *et al* 2009). Table1 gives the typical plasmonic resonant frequencies of some metals.

Aluminium has low melting point and is a low cost reliable metal when compared to other metals and reflects all wavelengths from UV onwards. The approach analyzed in this paper to realize elliptical beam profile is to restrict the spread of optical power in the distal tip of an solid core PCF (SCPCF) through SPR effect at the metal/dielectric interface of metal infiltrated microholes of the PCF, along one dimension, and simultaneously allowing the power to spread in the perpendicular direction, through selective infiltration of the microholes in that direction, with infiltrate of refractive index of the silica core. The forthcoming sections show the different mode profiles that can be realized using this technique through the results of FEM study of SCPCFs with selective metal/fluid infiltration of a commercial large mode area SCPCF, LMA-20.

2. Beam Modifications through Selective filling of fluid and metal in LMA-20

If the metal (e.g. Al) is infiltrated selectively into four PCF micro holes in the first layer which is close to the core, two each on opposite sides of the first hexagonal

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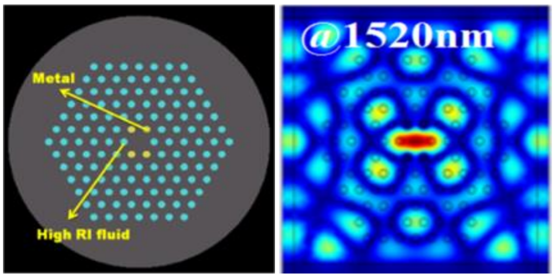
layer of microholes (as shown in Fig.1), it will offer tighter confinement of optical power of electromagnetic waves perpendicular to the this side due to plasmonic reflectance at the metal silica boundary leading to a comparatively elliptical profile. The ellipticity however will be limited as the air-filled holes surrounding the central core region will restrict the mode from spreading out into the microstructure of the silica cladding. If all the other holes are infiltrated with moderately higher index fluid (close to silica index) optical power will then spread sideways and into the silica region.

LMA-20 Solid Core PCF from Thor Labs has been taken up for simulation studies using finite element modeling. The effectively low index cladding of this SCPCF is realised using a microstructure consisting of six layers of 6.2μm air-holes arranged in triangular packing around a central 20μm silica core. A pair of neighboring microholes in the first layer and another pair located diametrically opposite on the other side of the core (Refer to Fig, 1(a)) is assumed to be filled with Aluminium with all the other holes filled with material index of silica core This will lead to confinement of power in one direction accompanied by spreading in the perpendicular direction. Fig. 1(b) shows the resulting elliptical beam profile with minor axis perpendicular to the metal infiltrated layers. But the simulated mode pattern also shows the losses due to power spreading into the silica regions of the cladding. Effective mode index from the FEM studies for input wavelengths covering the 1500nm-1550nm band shows that the RI is indeed complex with an imaginary part in the order of 10^{-6}. Beam modification is observable at all wavelengths, but is more elliptical with lower losses for shorter wavelengths near 1510-1520nm (refer Fig. 2(a) & Table2).

Table 1 Plasma frequency of standard metals

Metal	Plasma frequency (ω_p) [s−1] (Laukkanen et al)
Gold (Au)	13.8×10^{15}
Silver (Ag)	14.0×10^{15}
Copper (Cu)	13.4×10^{15}

The best aspect ratio of MFDs achieved (ratio of MFD's along the minor and major axis) is 1: 1.67.



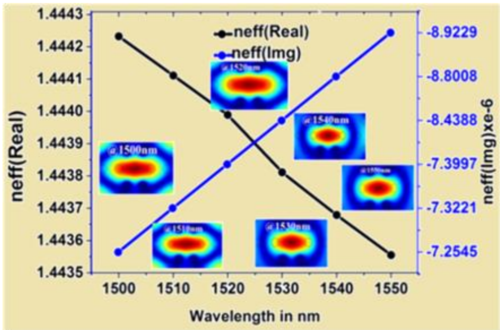
1 (a) 1(b)

Fig. 1(a) Schematic of metal infiltrated LMA-20 **1(b)** SPR based confinement in fully infiltratedLMA-20

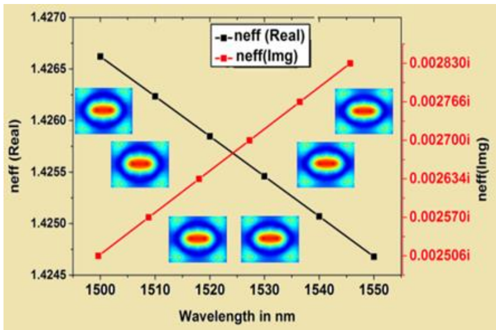
Table 2 Complex effective index of elliptical modes in metal/fluid infiltrated LMAPCF

Wavelength (nm)	n_{eff} (Real)	n_{eff} (Img)
1500	1.444232	7.2545e-6
1510	1.444111	7.3221e-6
1520	1.443989	7.3997e-6
1530	1.443811	8.4388e-6
1540	1.443679	8.8008e-6
1550	1.443555	8.9229e-6

The same trend is observed in the case of an LMA-20 tapered without hole collapse to 1/10th of its original dimension and then infiltrated with metal and high index fluid. As shown in Fig 2(b) the real part of the effective indices are lower but imaginary part is much higher indicating higher losses. Tapering will be a necessity in order to reduce the mode sizes to be compatible with that of the lower cross-sectional areas of the planar waveguides.



2(a)



2 (b)

Fig. 2 Variation of effective index with wavelength in metal based infiltrated (a) LMA SCPCF & (b) Infiltrated LMA Taper

3 Low-Loss Beam Modifiers using Metal Infiltrated Tapered LMA PCF

Tapering offers an easy way to decrease the mode-field diameter (MFD) of fibers, thereby allowing for a better coupling efficiency to the input of the waveguide. The profile of a tapered LMAPCF from 13.2 μm to 1.32 μm in pitch (from 20 μm to 2 μm in core diameter, correspondingly) with a relative air hole diameter d/10 = 0.64 μm are displayed. In order to reduce the MFD to around 2μm, the LMA-20 needs to be tapered before infiltrating with metal. Effective low loss planar beam modifiers that can focus the optical power from an input 2μm transverse dimension to 200nm-240nm width of rectangular waveguides can be realized on planar platforms. Therefore it becomes necessary to provide as an input to the planar platform a beam confined to 2μm.

3.1 Metal Filled Tapered LMA-20 with Air holes

When metal filling is done as shown in Fig 3 in the tapered fibers, leaving the rest of the microholes with air, a close look at the resultant mode pattern shows that it is a distorted hexagon with mode field penetrating in between the metal filled holes, but confined well within the core in the other directions. The MFD in this direction is 2.775μm, 0.775μm more than the core diameter. However when all the micro holes other than the metal filled ones are infiltrated with fluid of RI equal to the silica core, the mode spreads out laterally giving an elliptical profile as seen in Fig 4(c). But the losses are higher as mentioned in the previous section due to the power spreading into all silica regions.

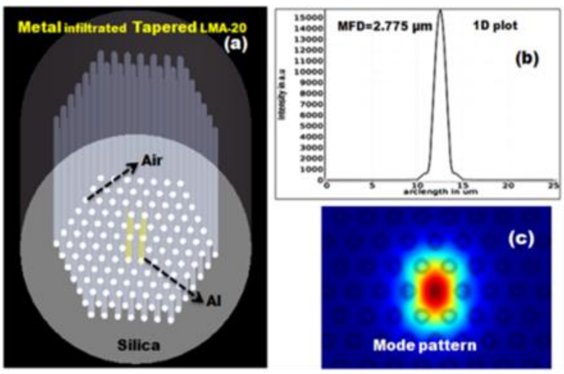


Fig. 3 Metal filled LMA-20 Taper with air holes

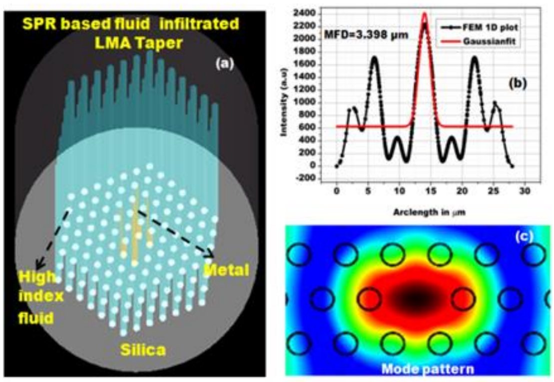


Fig. 4 Metal /high index fluid filled LMAPCF Taper

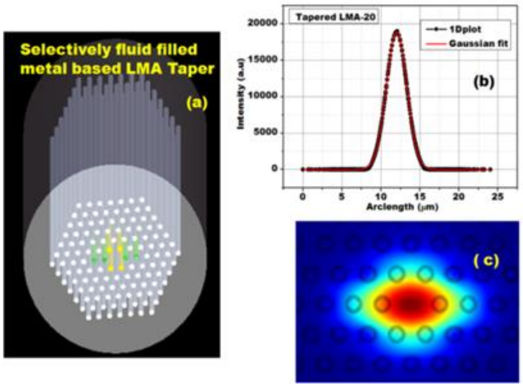


Fig. 5 Selective metal (yellow shade)/high index fluid RI (green shade) filling in LMA Taper (b) resulting elliptical mode pattern with fluid RI=1.4444 in LMA-Taper

If the high index fluid filling is done selectively as depicted in Fig. 5(a), the mode sustained within takes on a more elliptical pattern with the power extending to nearly 3Λ along the direction it sees silica index.

Losses are lower in this scheme as the effective low index provided by air-holes in all other directions constrains the field from penetrating into the rest of the silica region in the cladding microstructure. Thus an aspect ratio of nearly 1:2 can be achieved. Fig 6 shows that if a similar selective infiltration is done in the LMA-20 without tapering the resulting mode profile is much more elliptical in shape and the aspect ratio achieved is 1:3.

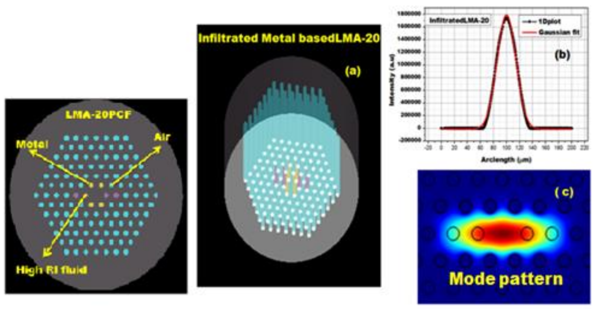


Fig .6 Selective metal (yellow shade)/high index fluid RI (violet shade) & (b) resulting elliptical pattern With RI-1.4444

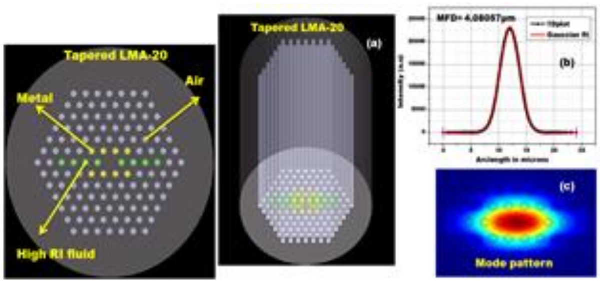


Fig. 7 Selective metal (yellow shade)/high index fluid (green shade) filling to generate LP01 mode pattern

To bring about a similar near elliptical beam profile the metal infiltration (yellow shade) is extended to four consecutive holes on either side of the central silica core, and high index fluid (RI = RI of silica) is filled along the sides (green shade) as depicted in Figure 7, then the mode profile is more elliptical with power extending laterally up to 3Λ into the region with silica index. The aspect ratio of the MFD is only 1: 2.06, lesser than what can be easily achieved with un tapered LMA. If RI of fluid is made high say 1.85, mode pattern changes as the high RI on the side's confines the beam back to the centre as shown as in Fig. 8.

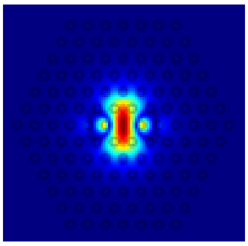


Fig.8 Mode pattern with fluid of RI 1.85

Thus the RI of the fluid infiltrated selectively into the microholes close to the core and the filling pattern will decide the resulting beam profile. If an electro-optic material is infiltrated selectively into the holes then RI can be tuned leading to a field dependent control of beam shape.

The degree of ellipticity (θ) achieved can also be quantified in terms of the tangent of the ratio of the minor to major elliptical axis, and is tabulated for LMA taper, metal based LMA taper and for metal based high index fluid infiltrated LMA taper as depicted in Table 3.

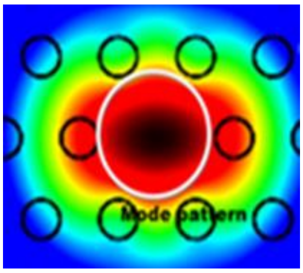


Fig .9 Mode elongation in metal based LMA taper fully infiltrated with high index RI

3.2 Results and discussions

The output mode field of the LMA taper with diameter MFD_{out} (2microns) is subsequently launched into the waveguide and the propagation along the waveguide can be monitored by employing suitable methods. The MFD is equal to2.775µm when the RI of SiO2 is 1.444 at wavelength is 1550 nm. Ellipticity is calculated for various LMA tapers which include untapered LMA-20 and given the details in Table.3.

Table 3 Ellipticity comparison among different LMA tapers

Type of LMA fiber& LMA Taper	MFD in µm along		Aspect ratio	$\theta = Tan\left(\frac{minor\ axis}{major\ axis}\right)$
	Minor axis	Major axis		
LMA-20 Taper	2.298	2.785	1:1.212	0.01439
Metal based LMA-20 taper	2.334	3.892	1:1.668	0.0104
Metal based fully filled LMA Taper	3.038	3.398	1:1.118	0.0156
Selective Metal(4holes)/high RI fluid filled taper	3.717	5.932	1:1.595	0.0109
Selective Metal (8holes)/high RI fluid filled taper	1.9802	4.080	1:2.061	0.0085
Selective Metal/ high RI fluid filled LMAPCF	19.400	56.44	1:2.909	0.006

Comparison of all these mentioned micro structures concluded with achievement of high aspect ratio and suggesting the specific fiber tapers for mode transformers and figured out to be applicable as a key source element.

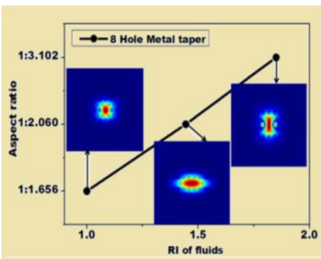


Fig.10 RI based tuning of aspect ratio for the same configuration of 8 metal filled and 8 tunable material infiltrated holes with beam profiles as inset

4. Application of LMAPCF Based SPR Beam Modifiers for Coupling to Planar Silicon Waveguides

The optical power from an optical source or standard SMFs can be connected to appropriately tapered and selectively metal/fluid infiltrated PCF such that the minor axis is aligned along the width of the wafer. The mode modifier in turn is attached to a planar waveguide (designed for single mode transmission), 240nm wide, 10 microns deep and 5 microns long. An elliptical mode with minor axis 240nm wide is obtained as the waveguide output. The elliptical mode suits a high aspect ratio planar waveguide for integrated optics based applications A source at (1520-1570 wavelength range) is connected to input the LMA Tapered fiber that is subsequently placed in front of the rectangular waveguide. The core diameter of the

LMA Taper is 0.64 microns with pitch nearly equal to 1.32 microns. On chip 2D planar beam modifier will reduce the 2μm dimension to 240nm as illustrated in the COMSOL simulation result shown as an inset of Fig, 11.

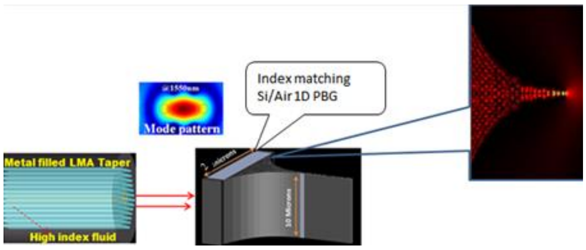


Fig. 11 Proposed schematic of LMA PCF based SPR beam modifier for optical interconnection to silicon waveguides

Conclusions

SPR based optical interconnects to be used in silicon photonics have been studied. Elliptical beam profiles have been realized using SPR effect and selective fluid infiltration. Possibility of achieving aspect ratios of 1:3 or higher has been demonstrated through simulation. Programmable beam profiles modifications can be achieved through RI tuning of the infiltrates.

Furthermore, a significant improvement is expected if a microstructured fiber with an elliptical core is employed. In particular, the elliptical core allows for preservation of the polarization while matching the width of the output mode of the fiber with the horizontal dimension of the fundamental mode of the waveguide and minimizing the height difference.

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