Abstract—The characterization of silicon microspheres coupled to Si waveguides at telecom wavelengths, on a Silicon-On-Insulator technology based chip, is presented. The transmittance signal through the waveguides is strongly attenuated (up to 25 dB) at some frequencies. This effect is attributed to the coupling of light to the microspheres at wavelengths corresponding to their Mie resonances.

Keywords- silicon microspheres; microcavities; Silicon-On-Insulator technology; modal analysis; optical coupler; optical filter

I. INTRODUCTION

Optical microcavities are very relevant structures for optical processing of light, because they can trap and confine electromagnetic energy during long times in very reduced volumes, enhancing this way light-matter interaction [1]. Among the different technological platforms on which microcavities can be produced, silicon is of uttermost importance because it can combine electronics and photonics at the same time in a single device [2]. Recently, some of us reported on the synthesis of silicon microspheres, also called silicon colloids [3]. They are highly spherical particles with diameter from 0.5 to 5 µm and with a very smooth surface. This allows them working as photonic microcavities, with well defined Mie modes. The spectral characterization of these modes was also realized by means of Fourier Transform Infrared spectroscopy (FTIR) [3].

Here, we report on the coupling of silicon microspheres to Silicon-On-Insulator (SOI) waveguides at telecom wavelengths (C-band). For this purpose, devices consisting of SOI waveguides with microspheres deposited onto them are developed and their transmitted signal is measured. These measurements are compared with theoretical calculations of Mie modes of the microspheres. Previous reports about similar devices include 2D photonic crystal (PC) nanocavities coupled to PC waveguides [4], ring shaped cavities coupled to SOI waveguides [5], and half millimeter diameter silicon spheres coupled to optical fiber half couplers [6].

II. EXPERIMENTAL PROCEDURES

The silicon waveguides for this study have a cross section of 500x220 nm². They were produced on a standard SOITEC wafer by deep UV lithography in an ePIXfab platform. Their length is about 3 mm and they finish at their both ends by a grating coupler so that light can be easily in/out coupled to/from the waveguides [7]. Both, waveguides and couplers were designed for transmitting only TE polarized light around 1550 nm. Light from an ASE source was coupled to the waveguide and the transmitted signal was measured by an spectrum analyzer.

Silicon microspheres are obtained by chemical vapor deposition means, using di-silane as a precursor gas [3]. This method allows synthesizing amorphous and poly-crystalline silicon microspheres. For this work, poly-crystalline microspheres were chosen. Because the as-grown samples consist of a substrate with many isolated and clustered spheres and because some of them have defects, we observed the microspheres by optical microscopy and sort out the bad ones. Also, because the spheres are poly-disperse with sizes from 0.5 to 5 micrometers, we performed a selection of spheres (within the limited resolution of the optical microscope at 1000x magnification) having a diameter from 2.0 to 2.5 micrometers approximately. This is very important because the size of the sphere determines which resonant modes posses a frequency within the transmission wavelength range of the silicon waveguide and can therefore be coupled to it.

Optical transmittance measurements were performed on the selected microspheres, one by one, in a wide wavelength range, namely from 1 o 4 micrometers. We used a Fourier Transform Infrared Spectrometer Bruker IF 66/S for that purpose. This allows identifying the resonant modes and determining precisely the sphere diameter by fitting the measured signal to Mie theory [3]. Therefore, only those microspheres having resonant modes within the transmission range of the waveguides were considered as candidates to build up the devices.

Finally, the placement of the candidate microspheres on top of the silicon waveguides was realized by micromanipulation techniques. Different needle-shaped tools were fabricated for the pick and place operation and for the fine positioning of the spheres on the waveguides.

III. RESULTS AND DISCUSSION

Figure 1 shows an optical microscopy image (top view) of a Si microsphere on top of a waveguide. The diameter of the sphere, determined by the procedure described above, is 2490 nanometers. The inset shows the direction and the polarization of light with respect the waveguide-microsphere device.
Figure 1. Optical microscopy image at 1000x magnification of a silicon microsphere placed on top of a silicon waveguide. Inset, schematic of the sphere and the waveguide showing the polarization of the transmitted light.

Figure 2. Measured light transmittance through a silicon waveguide with a silicon microsphere positioned on it (solid line, left axis). Simulation of the transmittance of the same silicon microsphere being isolated (dashed line, right axis).

Figure 2 shows the transmitted light through the waveguide with the microsphere placed on it (solid line, left axis), as well as the calculation by Mie theory of the transmission of light that would produce the same microsphere being isolated, i.e. without being placed on any substrate (dashed line, right axis). The deeps in transmission in the last case correspond to whispering gallery modes (WGM) that are indicated in the figure by letters ‘a’ and ‘b’ for TM and TE modes respectively, followed by two sub-indexes that account for the mode order [3]. We have associated the deeps in the transmitted signal through the waveguide to the coupling of light to the resonances of the microsphere. This way, the pronounced deep placed around 1535 nm would be originated from b_{10,1} mode and the much wider deep placed around 1580 nm from a_{6,2} mode. However, some discrepancies between theory and experiment are present. Some modes like a_{9,1} and b_{7,2} did not give rise to a coupling effect and the coupled modes (b_{10,1} and a_{6,2}) split into two deeps respectively. Several reasons may account for these discrepancies. Firstly, while in the calculation the sphere is considered to be isolated, in the experiment it is placed on the silicon waveguide, therefore mode degeneracy would be broken due to the waveguide coupling. Secondly, the control on the position of the microsphere is limited in the direction perpendicular to the waveguide, thus different coupling effects can be produced depending on this position. Thirdly, the microsphere may have some defects that could not be detected by optical microscopy and some type of absorption could be present. This would decrease the quality factor of the resonances. Nevertheless, it should be stressed the strong and peaked attenuation of the signal, of about 25 dB, achieved around 1535 nm.

IV. CONCLUSIONS

We have demonstrated the coupling between a silicon waveguide and a silicon microsphere. The light transmitted through the waveguide has been attenuated up to 25 dB for a wavelength corresponding to one of the microsphere resonating modes. A splitting effect of the modes has also been observed.

ACKNOWLEDGEMENT

The authors wish to acknowledge financial support from projects MAT2006-03097, Consolider Nº 18411 Nanolight.es, and TEC2008-06145 of the Spanish Education and Science Ministry, project PROMETEO/2008/092 of Generalitat Valenciana and project Apoyo a la investigación 2009 from Universidad Politecnica de Valencia, nº reg. 4325. J.D. Doménech acknowledges the FPI research grant BES-2009-018381. E. Xifré-Pérez acknowledges the financial support from the program Juan de la Cierva (Spanish Ministerio de Educación y Ciencia).

REFERENCES