Fabrication and characteristics of low loss and single-mode channel waveguides based on DNA-HCTAC biopolymer material*

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A novel biopolymer, deoxyribonucleic acid-hexadecyltrimethylammonium chloride (DNA-HCTAC), is used as the core layer material in optical waveguide, and the cleanroom technology is successfully applied to fabricate the single-mode channel waveguides with low propagation loss. The prepared DNA-HCTAC material shows high optical quality at the optical telecommunication wavelengths, such as high transparency, relatively high refractive index and low birefringence. In the fabrication approach, polymethyl methacrylate (PMMA) is used as a barrier layer to protect the DNA-HCTAC material from the corrosive of photoresist developer, and the etching conditions are optimized to form the smooth wall and sharp cross-section of the waveguide. Lastly, the optical characteristics of DNA-HCTAC channel waveguides are measured. The results show that the DNA-HCTAC waveguide operates with single-mode propagation and has a low optical loss.
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It is well-known that deoxyribonucleic acid (DNA) is a long polymer made from repeating units called nucleotides, and is researched extensively in medical and biological fields[1]. However, it is surprising that in the past two decades, novel optical biopolymer materials, such as DNA with cyltrimethylammonium and DNA with poly(3,4-ethylenedioxythiophene)/poly(styrenesulfonate) complexes, have received more attention for their excellent optical properties[2-4]. And DNA-based biopolymer materials offer many advantages for the fabrication of photonic devices, such as low cost, tailor-made properties and simple processing steps, which have obtained many applications in the fabrication of photonic devices, including bio-organic light emitting diodes[5], bio-organic multimode interference waveguide splitter[6], bio-organic field effect transistors[7], bio-organic electro-optic modulators[8], and optical amplifier with Eu^{3+}-doped DNA-based biopolymer[9].

On the other hand, for the photonic devices with integrated light circuits, the channel waveguide is a kind of fundamental element as a connector between optical blocks. Based on the excellent optical qualities of DNA-based biopolymer and the variable polytechnic methods[10], it is worth to explore the fabrication process of the channel waveguide with the polymer and biopolymer materials[11,12]. In this work, a new optical biopolymer, deoxyribonucleic acid-hexadecyltrimethylammonium chloride (DNA-HCTAC), is prepared, and a low loss and single-mode channel waveguide based on the DNA-HCTAC biopolymer has been fabricated by using the cleanroom technology with the optimized reactive ion beam etching conditions. Since the DNA-HCTAC biopolymer material can be damaged by the photoresist developer solution in the photolithography process, a polymethyl methacrylate (PMMA) barrier layer is used to protect the DNA-HCTAC from the corrosive of photoresist developer, which leaves the PMMA barrier layer as up-cladding layer of the waveguide. Finally, the optical characteristics of the biopolymer channel waveguide are successfully measured with our planar waveguide test platform.

For preparing the DNA-HCTAC biopolymer material, the thread-like DNA material with an initial mean molecular weight (MW) >1300 kDa, which is extracted from the salmon tests, is purchased from Aldrich corporation and used without further purification. For consistency, the MW of DNA in terms of base-pair (bp) is 660 g/mol/bp, and the width of a base pair is a third of a nanometer, so the MW of DNA of 1300 kDa corresponds to 2000 bp, and an average DNA chain

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length is about 0.75 μm. In order to make a possibility for formatting thin film and fabricating waveguide structures with DNA biopolymer, it needs to change the solubility of DNA by using a cationic surfactant to convert DNA to a DNA-lipid complex. We precipitate DNA with HCTAC, which is bought from Fluka corporation, to form DNA-HCTAC complex by the ion exchange method[13,14]. DNA-HCTAC is insoluble in water but soluble in many alcohols, including methanol, butanol and alcohol/chloroform blend.

At first, 0.5 g of DNA were dissolved in 500 mL distilled water at room temperature, and magnetic stirrer was used for making the DNA dissolved in water uniformly. Then an equal amount by weight of HCTAC were likewise dissolved in distilled water also at a concentration of 1 g/L. Next, the DNA solution was added drop-wise to the HCTAC solution with a burette, so that a white DNA-HCTAC precipitate was formed, and the mixed solution was set in refrigerator for several additional hours, in order to ensure the reaction was sufficient. The precipitate was collected by using centrifuge and pouring the upper liquid away from the centrifuge tube. Then another 1−2 L distilled water was added for washing the collected precipitate to thoroughly remove the remnant non-reaction HCTAC. In succession, the precipitate was put into a beaker to be dried in an oven for more than 30 h at the temperature of 80 °C. Finally, the dried DNA-CTMA powder was dissolved in butanol (99.9%) by using magnetic stirrer at about 80 °C for 24 h to make sure the powder dissolved sufficiently in the butanol solution, and the butanol solution with DNA-HCTAC was filtered through a filter with a pore size of 0.8 μm. It should be pointed that the butanol was selected as a solvent because of its slow evaporation with a high boiling point (116−118 °C), which ensures to form a smooth uniform thin film during the spin-coating process for the fabrication of waveguide.

The absorption spectrum of DNA-HCTAC butanol solution is shown in Fig.1, which is measured with a UV/VIS/NIR spectrometer at room temperature. It can be seen that the solution has a strong absorption for the wavelengths shorter than 300 nm, but there is almost no absorption for the longer wavelengths. Hence, we can expect that the DNA-HCTAC thin film is transparent for the communication wavelengths. In addition, DNA-HCTAC thin films are formed with spin coating method for the measurement of its refractive indices. Fig.2 shows the variations of the refractive index of DNA-HCTAC film at different wavelengths, which is determined by using a prism coupler[15]. It can be seen that the refractive indices of DNA-HCTAC thin film are 1.48459 (TE mode) and 1.4839 (TM mode) at 1550 nm and 1.4984 (TE mode) and 1.4977 (TM mode) at 632.8 nm.

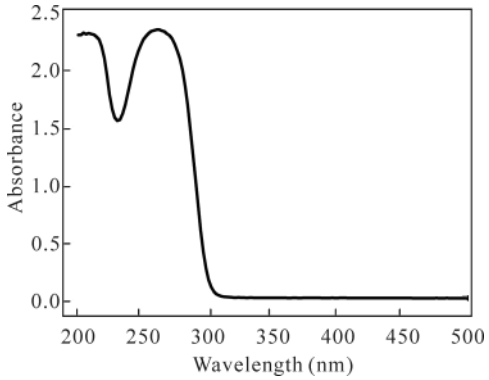

Fig.1 Absorption spectrum of DNA-HCTAC butanol solution

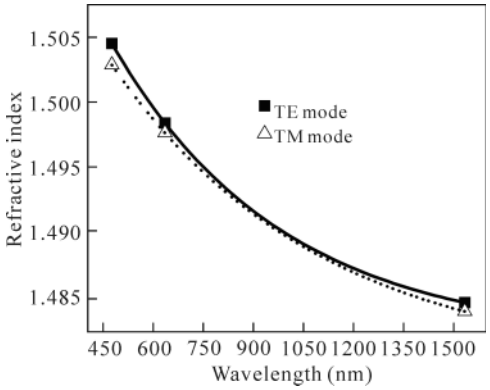

Fig.2 Refractive index of DNA-HCTAC film as a function of wavelength

To fabricate single-mode channel waveguides with DNA-CTMA biopolymer material, the traditional cleanroom technologies are used[16,17], and the fabrication processes are shown in Fig.3. At first as shown in Fig.3(a), a core layer (thickness of 3 μm) of the waveguide was formed by spin-coating the DNA-CTMA butanol solution onto the Si substrate, which has a 7 μm SiO_2 layer as the bottom cladding layer of the waveguide. And then, the DNA-CTMA film was cured at 110 °C for 1 h by using a hotplate. Secondly, as shown in Fig.3(b), the PMMA polymer/toluene solution, which has a low refractive index of 1.46 at 1550 nm, was spun on the DNA-CTMA film as a cover layer of the waveguide. And the PMMA layer with the thickness of 5 μm was also cured at 110 °C for 2 h. In fact, the PMMA layer also acts as a protecting layer to prevent the DNA-HCTAC biomaterial from the damage of photoresist developer solution in the later photolithography process. In the step of Fig.3(c), a chromium layer with the thickness of about 100 nm was sputtered on the PMMA layer by radio frequency (RF) sputtering, and then the sample was covered with a photoresist layer and cured at 90 °C for 10 min. Next, exposure was performed using the mask aligner contact printer as shown in Fig.3(d), and the exposure time is 10 s based on the 350 W lamp intensity. The photoresist was then developed with AZ 300 MIF developer solution in

a beaker. Due to the PMMA barrier layer, sufficient exposure of the photoresist cluld be performed to fully bring out features in the photoresist, and it did not damage the DNA-HCTAC core layer. For transferring the stripe patterns to the DNA-HCTAC layer, the Cr layer without covering of photoresist was removed by using wet etching technique as shown in Fig.3(e), and then the channel waveguides were fabricated by the reactive-ion-etcher (RIE) system at an optimized recipe to mix the gas of CF_4, SF_6 and O_2 with the ratio of 1:1:5. The chamber pressure was 30 mTorr, and the RF power was 90 W (Fig.3(f)). Lastly, the DNA-HCTAC channel waveguides were formed by cladding of PMMA layer. Fig.4 shows the photo of a 10-μm-wide channel waveguide with upper and lower claddings by scanning electron microscope (SEM). We can see the channel waveguide has a sharp profile with very smooth surfaces and vertical sidewalls, which implies a better confinement of light in the waveguide and a low scattering loss along the waveguide.

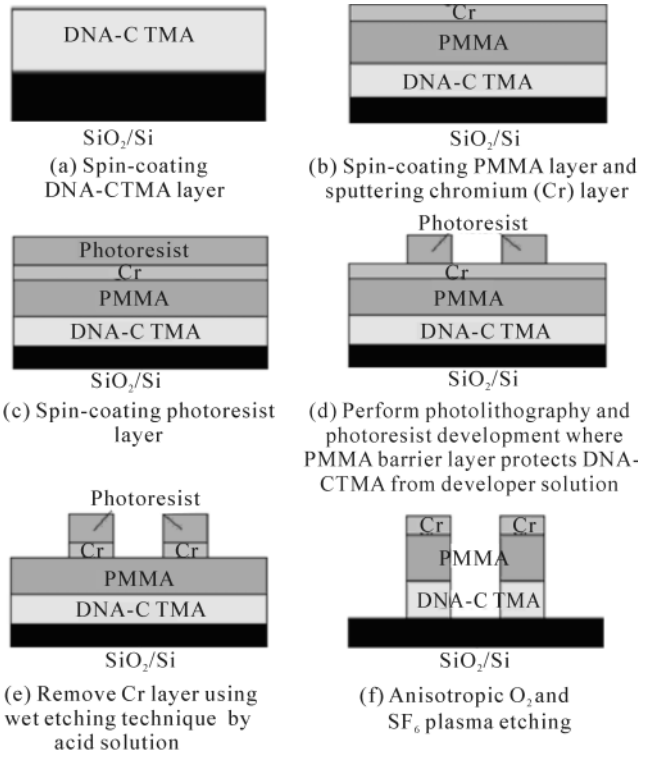

Fig.3 Fabrication steps of the channel waveguide with DNA-HCTAC biopolymer

For telecommunication applications, the optical characteristics of the DNA-HCTAC channel waveguide were measured with our planar waveguide test platform for different wavelengths. The stable semiconductor laser was used as the light source, the output light of the laser was coupled into the waveguide through a single-mode fiber by end-fire technique[18], a 20 times object lens was applied for output coupling of the

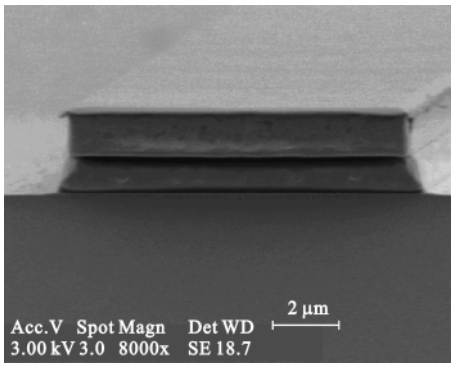

Fig.4 SEM image of a DNA-CTMA channel waveguide

waveguides and the output single mode of the waveguide was measured on the monitor of the CCD camera. Fig.5 shows the near-field mode pattern at the output end of the DNA-HCTAC channel waveguide, which confirms that the waveguide is of single-mode operation at 1550 nm. Then, the propagation loss of the waveguide was measured by the cutback method[19]. The measured propagation losses of the DNA-HCTAC channel waveguide are 0.82 dB/cm at 1550 nm, 0.64 dB/cm at 1310 nm, 0.81 dB/cm at 980 nm, and 0.62 dB/cm at 633 nm, respectively. It should be pointed that each loss value above is an average value, which is measured more than five times for the stability of experimental processes.

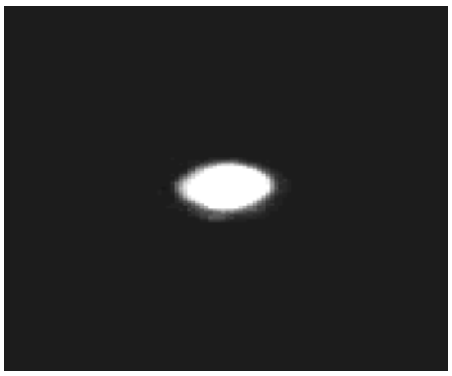

Fig.5 Single-mode pattern on the monitor of the CCD camera system

In conclusion, the low-loss DNA-HCTAC channel waveguide is successfully fabricated by using cleanroom technology, such as spin-coating, photolithograpy and RIE processes. A new approach utilizing a PMMA barrier layer for protection against damaging from photoresist developer is used, and the low refractive index PMMA is left as cladding layer. It is important to ensure the high quality of the cross section profiles and very smooth surfaces of the DNA-HCTAC channel waveguides. And the experimental results exhibit the good performance of the channel waveguides with a low propagation loss and a single-mode operation at the wavelength of 1550 nm. This work sets a basis for the fabrication of DNA-

HCTAC photonic devices, and demonstrates the application foreground of DNA-HCTAC biopolymer material in photonics.

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