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Forward-looking Intravascular Ultrasound Catheter with an Electromagnetic Micro-Motor

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***Abstract*—Current commercial side-looking intravascular ultrasound catheter utilizes long flexible shaft to rotate the transducer for intravascular imaging. However, due to the characteristic of the side-looking intravascular ultrasound catheter, it cannot be used for imaging of chronic total occlusion. Furthermore, using an external motor to drive the transducer will cause non-uniform imaging distortion. An effective way to solve these problems is directly driving a forward-looking transducer to work by using a distal micro-motor. In this study, a catheter consists of an electromagnetic motor and a high-frequency forward-looking transducer was developed. The ionic liquid was used as the wire to connect the transducer and the ground. The prototype of catheter that fabricated in this study has a 2 mm outer diameter, and the motor has a maximal speed of the 275 PRS.**

Keywords—intravascular ultrasound(IVUS), distal actuator, electromagnetic motor, forward-looking IVUS, chronic total occlusion

I. INTRODUCTION

Atherosclerosis, a progressively serious lesion based on lipid metabolism disorders, could cause the arteries to gradually narrow. This disease is not easy to be recognized in its early stage, but when people feel uncomfortable, the blood vessels tend to be severely narrowed or even completely blocked, forming the chronic total occlusion (CTO). CTO is so common that about 20% of the patients in coronary angiography has such disease [1]. In the past, diagnosis and treatment of coronary artery disease mainly used coronary angiography and side-looking intravascular ultrasound (SL-IVUS) imaging catheter. Angiography can detect the location of the CTO lesion while SL-IVUS catheter can provide the detailed information of the disease. However, the SL-IVUS should pass through the lesion area to implement imaging, which cannot be applied when the blood vessel is completely occluded. Moreover, X-ray is used in angiography for imaging, means harmful for our body when exposed to radiation for a long time [2].

To overcome these drawbacks, the concept of forward-looking intravascular ultrasound (FL-IVUS) was developed. It can implement imaging for CTO. The earliest FL-IVUS catheter utilized a flange which rotated by a cable that drives the pin to generate a sinusoidal motion for transducer, and thus the image of blood vessel can be achieved. This drive mechanism is complex, which makes the size of the catheter large [3]. In order to reduce the diameter of the catheter, the capacitive micromachined ultrasonic transducer (CMUT) technology that combines transducers with integrated circuit was developed. However, the arrays of transmit and receive are separate, significantly increasing the processing cost. And so far, the highest frequency of reported CMUTs is approximately 20 MHz [4-5]. To improve the quality of images, the forward-looking phased-array transducer was developed. The transducer has a high frequency and small size, but it is hard to fabricate and could not acquire the information of the blood vessel wall around the lesion [6]. The catheter consists of angled transducer and proximal motor was reported to overcome these limitation. The long flexible drive shaft was used to transmit rotation. Friction will occur between the wall of catheter and the shaft when the catheter pass through a long curve vessel, which leads to image distortion [7-8].

In order to eliminate these drawbacks, we have proposed a distal micro-motor integrated with a high-frequency transducer at the top of the catheter as shown in Fig. 1 [9]. The micro-motor has a simple structure that consists of three coils and a customized cork base as stator. An angled magnet is used as rotator. The final size of the micro-motor is 3.7 mm in length and 1.2 mm in outer diameter. The transducer is combined with the magnet to achieve forward-looking. The transducer signal line is connected to the transducer through the steel ball bearing and the magnet, and the ionic liquid is used as the wire, which indirectly connects the transducer with the ground. The novel structure of FL-IVUS catheter with a built-in motor can eliminate the non-uniform images and acquire more information of the disease. The tungsten wire target is used to assess the performance of the catheter, and the result shows that the FL-IVUS catheter has a good resolution in both axial and lateral direction.

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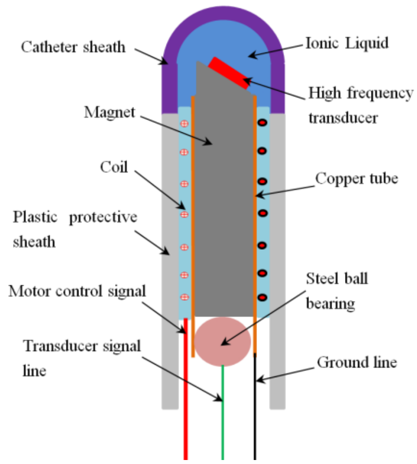

Fig. 1. Schematic diagram of the forward-looking intravascular ultrasound catheter based on the electromagnetic micro- motor.

II. METHODS

A. Design and fabrication of the micro motor

The micro electromagnetic motor is improved on the basis of the previous research in our lab [10], which has a maximal speed of 275 RPS. The input signal wire of transducer is connected with the motor by conductive silver glue (E4110). To prevent short circuit between the signal wire and ground of the transducer, the copper tube is insulated from the base, while an insulating film is bonded around the magnet. The final size of the micro-motor is 1.2 mm in outer diameter and 3.7 mm in length respectively.

B. Design and fabrication of the transducer

In order to meet the requirements of the intravascular ultrasound imaging catheter, the transducer should have high frequency and small size. The PMN-PT 1-3 composite single crystal (CTS Technology, USA) is choesn. The element is 0.5 mm × 0.5 mm in size, and 24 μm in thickness. The conductive epoxy (E-Solder 3022, VonRoll USA Inc.) is used as the backing material. The parylene (PD2010, Specialty Coating Systems) film is selected as the matching layer according to transmission line theory. A corner of the matching layer is removed and then covered with conductive silver glue, conducting the transducer with the copper tube through the ionic liquid.

C. Integration and drive of the Catheter

The transducer is integrated with the angled magnet by conductive silver glue. Then the magnet is put into the copper tube. The magnet is connected with cork base by magnetic force. By this way, the transducer and the input signal wire are indirectly connected. Ionic liquid is filled at the top of the catheter as the wire to connect the transducer with the tube. The final diameter of the catheter is 2 mm in outer diameter. The motor is driven by three sinusoidal signals with a 120° phase difference among them. The signal of the transducer can indirectly drive transducer to work through the micro-motor, due to the special structure. The pulser-receiver (5900PR, Olympus NDT Inc.) with energy of 1 μJ, and 1 kHz repetition rate is used to excite the transducer and receive pulse-echo signal.

III. RESULTS AND DISCUSSION

A. Electrical performance characherization

To verify the electrical performance of the transducer, the impedance and phase are tested. The signal wire is connected with the backing of the transducer by electric sliver glue. The surface of the transducer is then immersed into the ionic liquid, and a ground wire is placed close to the transducer as shown in Fig. 2(a). Using the same method as above, the impedance and the phase of the transducer that integrates into an angled magnet by silver glue is also tested (as shown in Fig. 2(b)). The results of the electrical performance test are shown in Fig. 3(a). and Fig. 3(b). respectively, which is significantly different from each other, for the reason that the transducer is fixed on a cylindrical magnet by conductive silver glue. Such structure can lead to a change in capacitance or inductance in the equivalent circuit, which affects the phase angle. In addition, the magnet also increases the impedance of the catheter.

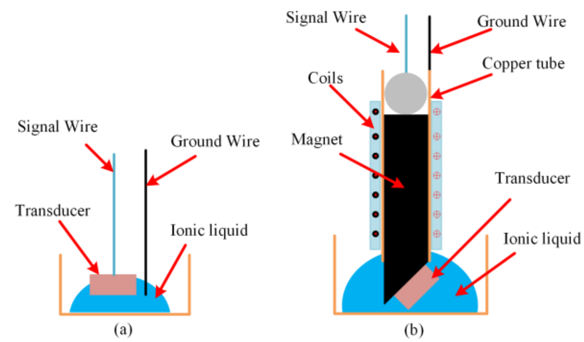

Fig. 2 Schematic diagram of the impedance and phase test. (a) Transducer and (b) Catheter

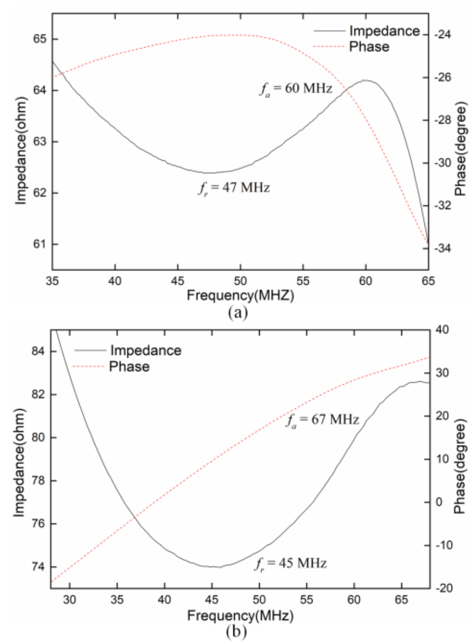

Fig. 3. Results of the impedance and phase (a) Transducer and (b) Catheter.

B. Acoustic performance characterization

The transducer and the FL-IVUS catheter is fixed on a holder, respectively, and are then immersed into a tank filled with deionized water. The stainless steel target is set in an angle to make sure the wave of the transducer perpendicular with the target surface. The pulse-echo result shows that the center frequency and -6 dB fraction bandwidth of the transducer is 44 MHz and 87% , while the center frequency and -6 dB fraction bandwidth of the catheter is 46 MHz and 88%, which can be seen in Fig. 4. The amplitude of the transducer is less than the amplitude of catheter, but no obvious difference between the center frequency and -6 dB bandwidth.

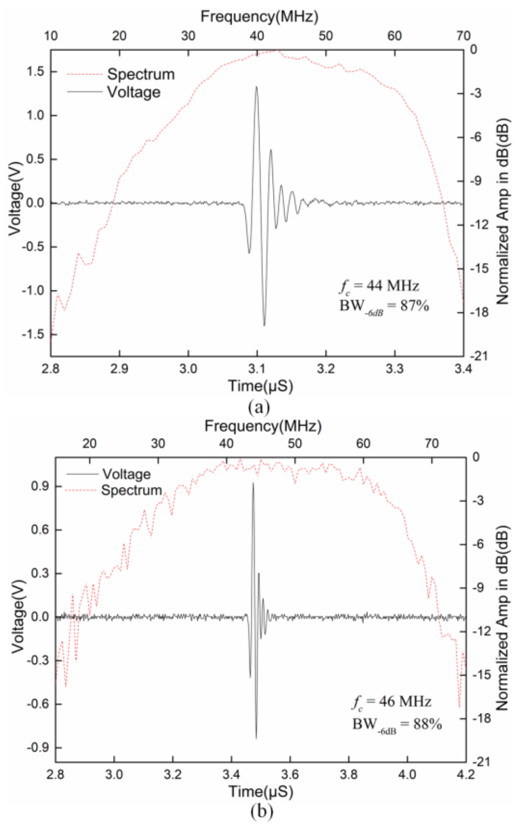

Fig. 4. Pulse–echo response and Fast Fourier Transform Algorithm spectrum. (a) Result of transducer (b) Result of catheter

IV. Conclusion

In this study, we presented a FL-IVUS catheter for CTO imaging. It consists of an electromagnetic micro-motor which has an angled rotator and a high-frequency transducer. The ionic liquid is used as the wire, integrating the motor with the transducer at the top of the catheter. The size of the prototype FL-IVUS is 2 mm (outer diameter). The micro motor has a maximal speed of 275 PRS, which can meet the requirements of the intravascular imaging. Applying such distal motor into the catheter can effectively eliminate image distortion. Although the electric performance test results of the transducer and the catheter vary widely, their pulse-echo results are similar, indicates that integrating the transducer on the magnet does not affect its acoustic performance. The bandwidth of the catheter is width, and it can acquire more information in the vessel. Further improvements can be made to the existing FL-IVUS, which can help the surgeon be more proficient at performing diagnostics and intraoperative guidance in the future.

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