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CASE STUDY

EP17HTND-CCM: Electro-thermal Actuated, Miniaturized Optical Scanning Fiber Endoscope

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Application

Endoscopes have had a revolutionizing impact in the field of medicine. Prior to their inception, routine diagnostic and surgical procedurals were more invasive requiring longer recovery times as well as a greater risk of complications. The advent of small, flexible endoscopes enabled physicians and surgeons to easily access internal cavities and the inside of vital organs.[1] Generally, endoscopes are composed of a flexible insertion tube, a light source for illumination, a lens system, and an image sensor. Through endoscopy, the doctor or surgeon can collect valuable diagnostic images from inside the body as well as perform other functions such as biopsies, cauterization, clipping/cutting, or foreign object retrieval. An obvious limitation of endoscopy is the diameter of the insertion tube—larger sized endoscopes can be used to access the nasal and ear passages, the gastrointestinal system, internal body cavities via incision, and other areas. However, particularly narrow areas such as peripheral airways of the lungs can be limited by the diameter of the endoscope insertion tube, necessitating more invasive and risky procedures such as transthoracic needle biopsies.[1]

Larger diameter endoscopes have a traditional illumination source and utilize a CCD or CMOS image sensor; however, as the size of the solid-state image sensor decreases, so does the image quality and resolution.[1] Below a 3 mm insertion tube diameter, miniaturization effectively requires too severe of a reduction in the size of the pixel elements and results in a significant loss of image quality. More recent approaches toward endoscope miniaturization utilize scanning fiber endoscopes (SFE) that can deliver relatively high image quality down to an insertion tube diameter of less than 2 mm. Despite this reduction in size, these technologies require further miniaturization before they can reach the narrowest of pathways found at the most distal ends of the airways where potentially cancerous nodules are most likely to be found.

Scanning fiber endoscopes (SFE) employ a clever design: a very thin, single-mode optical fiber emitting laser light is vibrated in resonance. This vibration results in deflection at the distal end of the fiber effectively scanning the image plane with the laser source. Additional optical fibers act as the detector collecting the backscattered light from the image plane. Oscillation of the fiber is accomplished via an actuator such as a piezoelectric crystal that imparts a radial vibration resulting in a spiral scan pattern.[1,2] Presently, for designs of this type, further miniaturization is limited by the size of the piezoelectric actuator.

To address the size limitations of the piezoelectric actuator, the authors of this study sought to explore a novel SFE design employing a thermal actuator and a laterally oscillating, micro-cantilever fiber as the laser source.[1] The micro-cantilever fiber is made by drawing a multi-mode optical fiber to a diameter of approximately 11 μm with subsequent splicing to the core of a dual-core fiber; only the thin, drawn portion of the fiber is vibrated. This dual-core fiber assembly is then proposed to serve both as the illumination source as well as the means by which to collect the reflected light. A total diameter of 0.5 mm, small enough to reach the distal airways, was targeted. The field of view is determined by the deflection distance or amplitude of the oscillation at the distal end of the laser-emitting fiber, and the unit itself rotates to create a 2-D image of the surface. See ***Figure 1***. Actuation is accomplished at the base of the micro-cantilever by a metal bridge that thermally expands and contracts based upon an applied electrical current. The assembly itself is seated and bonded with Master Bond EP17HTND-CCM epoxy within a 500 μm diameter hypodermic needle; a cap with an integrated lens system is used to ultimately seal the open end of the needle bore.

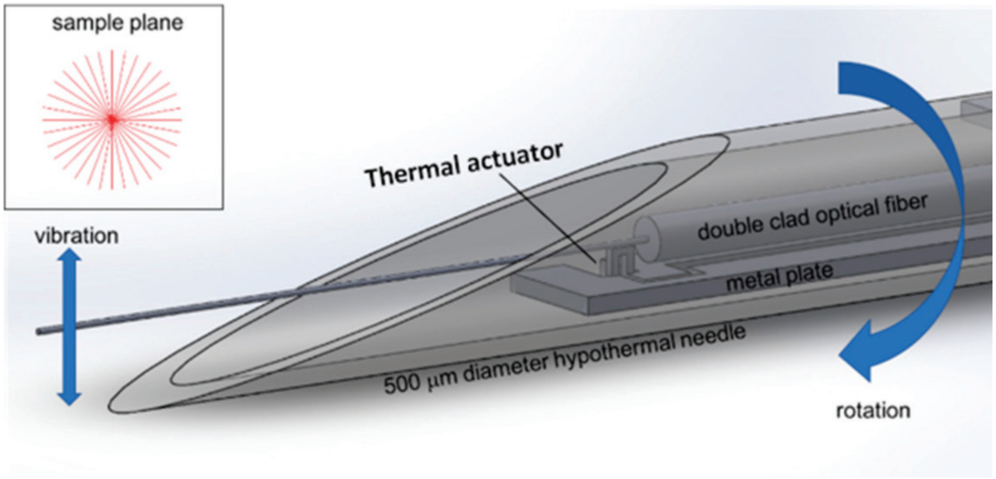

Figure 1. Schematic of the scanning fiber endoscope (SFE) with thermally actuated micro-cantilever fiber assembly seated inside of a 500 μm hypodermic needle. Insert shows proposed 2-D image generated from oscillation of the micro-cantilever laser source and rotation of the needle barrel. Not shown: Master Bond EP17HTND-CCM used to bond and seal assembly within needle bore.[1]

Key Parameters and Requirements

A thermal actuator, such as the one used in the construction of the novel scanning fiber endoscope, relies heavily on sound material selection. Primary criteria were linear coefficient of thermal expansion (linear CTE), thermal conductivity, Young's modulus, and electrical resistivity.[1] The principle of operation is as follows: electrical current is passed through a conducting wire to the fine-wire metal bridge that serves as the actuator, the temperature of the metal bridge is quickly increased due to resistive heating, the temperature increase of the metal bridge results in linear thermal expansion, this thermal expansion of the actuator impinges upon the base of the micro-cantilever resulting in vibration, this vibration results in displacement at the tip of the micro-cantilever optical fiber which effectively scans the laser-light onto the image plane. Optimization requires rapid heating and cooling with concomitant expansion and contraction of the actuator. The electrical current is applied periodically to the metal bridge such that it matches the natural frequency of the micro-cantilever fiber to induce resonance and to maximize the displacement at the tip of the micro-cantilever fiber. High resistivity and a large linear CTE of the metal bridge are critical for rapid heating and to provide an adequate degree of expansion. Further, this must be balanced with a high thermal conductivity to maximize heat conduction through the metal bridge as well as to speed the cooling process such that the temperature of the metal bridge returns to the starting temperature before the next current cycle. Additionally, the Young's modulus of the metal bridge must be high enough such that it resists bending, buckling, or deformation as the fiber vibrates. The authors selected pure copper for the conducting wire while aluminum 6061, aluminum 1199, and brass 7030 were chosen as bridge materials due to their optimal balance of material properties. See ***Figure 2*** for dimensions and details of the electro-thermal actuator (metal bridge). Simulations were performed to optimize for micro-cantilever tip displacement and temperature at the vibrating bridge junction.

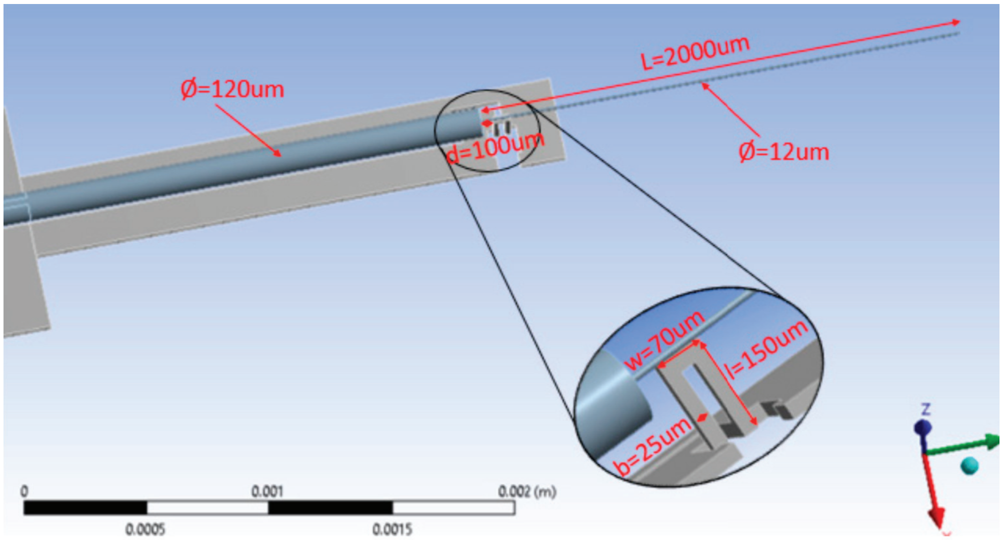

Figure 2. Device dimensions from simulated optimization experiments. Finite element analysis using ANSYS and COMSOL Multiphysics. Details of the electro-thermal actuator, metal bridge, shown in call-out.[1]

The small size of the device necessitated assembly of the components prior to insertion into the small bore, 500 µm hypodermic needle. A series of small polymer "collars" were fabricated using photolithography to aid assembly and alignment of the components.[1] To securely bond the components and to ultimately bond and seal them within the needle bore, a suitable adhesive was needed. Critical parameters for the adhesive were as follows: strong adhesion to metal and various polymers, minimal shrinkage or expansion during cure, high hardness and modulus, and a high glass transition temperature to avoid softening during high temperature operation of the device. Of particular importance is the hardness of the adhesive—it is critical that the adhesive does not dampen the vibrations of the micro-cantilever—further, the adhesive must have a high temperature resistance such that it does not soften at elevated temperatures and allow for vibration dampening. To maintain the precise alignment of the assembly, it is also critical that the adhesive has great dimensional stability during curing with minimal shrinkage or expansion.

The researchers carefully evaluated a wide variety of commercially available epoxy and acrylic adhesives; they determined that the one-component, heat curable epoxy, EP17HTND-CCM from Master Bond, was an ideal candidate.[1] In particular, Master Bond EP17HTND-CCM exhibited an excellent ~85 Shore D hardness, a high glass transition temperature, and a maximum service temperature up to 288°C (550°F). Additional benefits of Master Bond EP17HTND-CCM are its strong adhesion to a variety of substrates including polymers and metals, its great flow profile, low shrinkage upon cure, superb electrical insulation, and good thermal conductivity. The enhanced thermal conductivity of Master Bond EP17HTND-CCM further aids thermal management of this complex, electro-thermally controlled device. As a one-component epoxy system, Master Bond EP17HTND-CCM also offers great convenience during assembly.

It should be noted that the prototype endoscope outlined in this work would be destined for biomedical use. Master Bond has extensive expertise in formulating adhesive systems that are compliant with USP Class VI and ISO 10993-5 requirements for cytotoxicity.

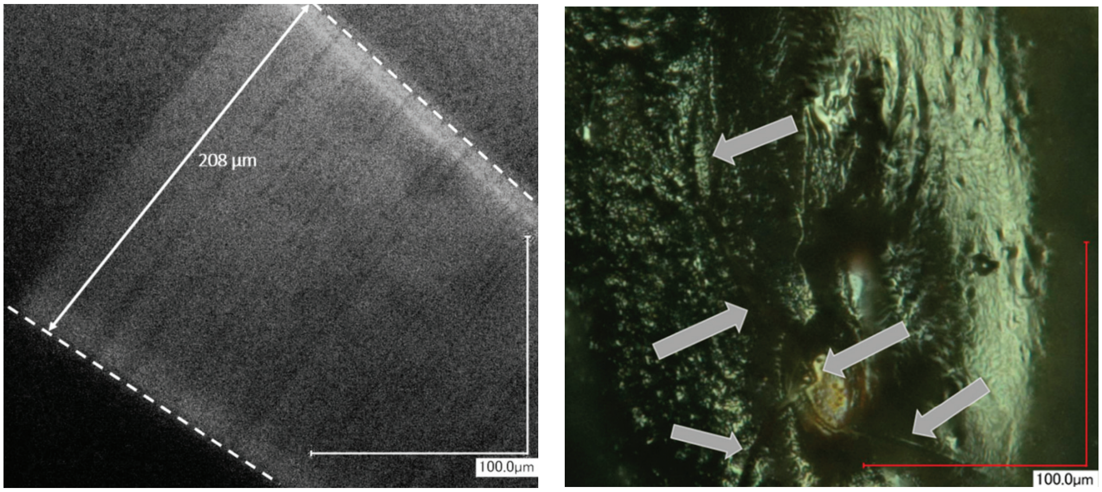

Figure 3. Left: tip displacement of the 2411-Hz brass sample at 0.461 W providing 208 µm of displacement. Right: thermally induced micro-cracks formed in the epoxy adhesive after hours of operations.

Results

The researchers found that their prototype devices constructed with Master Bond EP17HTND-CCM could reach the target diameter of sub-500 µm needed to access the distal airways of the lungs while achieving a tip displacement of 200 µm.[1] See ***Figure 3***. Further, achieved performance was comparable to that predicted via modeling. Compared with piezoelectrically actuated scanning fiber endoscopes (diameter: ~1.2 mm, length of distal ridge: ~10 mm), the prototype electro-thermally actuated scanning fiber endoscope outlined in this work is significantly smaller with a diameter of 0.5 mm and distal ridge length of 3-5 mm. The authors did note some difficulties with device longevity due to insufficient cooling and compromised structural rigidity when operating for extended periods. Insufficient thermal management in the device resulted in thermally induced micro-cracks in the EP17HTND-CCM epoxy adhesive after five hours of continuous operation. When cracks in the adhesive form, the rigidity is lost at the "fixed" end of the cantilever and vibrational dampening increases resulting in a loss of device performance. Despite this, the prototype device was found to be successful enough to warrant continued work and optimization.

Future work will seek to optimize the shape and size of the thin foil cut-out to better aid in heat dissipation, methods to improve the rigidity and temperature resistance at the back end of the assembly, and improvements to the repeatability of the manufacturing and assembly process. Also worthy of mention, it may be possible to further optimize the application of the epoxy adhesive as well as the cure schedule to further improve performance and robustness. To improve on the commercially available Master Bond EP17HTND-CCM, the engineers at Master Bond offer custom formulated solutions tailored to the demands of even the most challenging projects.

References

[1] Ahrabi, A. A., Kaur, M., Li, Y., et al. An Electro-Thermal Actuation Method for Resonance Vibration of a Miniaturized Optical-Fiber Scanner for Future Scanning Fiber Endoscope design. Actuators, 2019, 8, 21.

[2] Physik Instrumente, PI Americas. Miniaturized Piezo Tubes in High-Resolution Scanning Fiber Endoscopy. Accessed: April 28, 2023. URL: https://www.pi-usa.us/en/expertise/mini-piezoelectric-tubes-for-fiber-endoscopy