Fused micro-knots
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ABSTRACT
We present fusing of fiber micro-knot by CO\textsubscript{2} laser which fixes the micro-fibers in place and stabilizing the micro-knot shape, size and orientation. This fusing enables tuning of the coupling strength, the free-spectral range and the birefringence of the fiber micro-knot. Fused micro-knots are superior over regular micro-knots and we believe that fusing of micro-knots should be a standard procedure in fabricating fiber micro-knots.

Keywords: Fiber micro-knots, Fiber detectors

1. INTRODUCTION
Fiber micro-knots are simple but powerful devices for detecting temperature, moister, and acceleration.\cite{1,2} However, current fiber micro-knots parameters such as the coupling strength and the resonance frequency are set during fabrication and cannot be tuned later. Also, fiber micro-knot are fragile since the knot can tighten further till the fiber breaks under pulling. Therefore, we investigated a post-fabrication fusing of micro-knot. This fusing has three important effects on the micro-knot: First, by gradually increasing the fusing energy we can tune the micro-knot coupling strength to the critical coupling. Second, fused micro-knots are more robust and stable since the fusing locks the size, shape and orientation of the micro-knot. Third, fusing of the micro-knots changes the index of refraction and the stresses in the fiber which influence the resonance frequency and the free spectral range of the micro-knot. Therefore, we believe that fusing of fiber micro-knots is an important stage in micro-knot fabrication and should be a standard procedure in the micro-knots community.

2. EXPERIMENTAL SETUP AND RESULTS
First, we fabricated a simple micro-knot by tapering fiber to 3 \(\mu\text{m}\) diameter and tying a knot. Then, we pulled the fiber with a computerized translation stage while measuring both the spectral response and the size of the micro-knot with a microscope. Measuring the spectral response was done by sending broad-band light from a broad-band source into the micro-knot and measuring the output spectrum via an optical spectrum analyzer. A representative result of the transmission spectrum is presented in Fig. 1. From the transmission spectrum we obtain both the free spectral range and the amplitude spectral oscillations. The free-spectral range is a measure for the cavity length which is also measured via the microscope imaging according to:

\[
FSR = \frac{c}{nL},
\]

where \(c\) is the speed of light, \(n\) is the index of refraction and \(L\) is the length of the cavity.

A microscope image of the micro-knot is presented in Fig. 2. In this figure we present two images of the micro-knot from two orthogonal directions. The picture shows a clear image of the micro-knot. The micro-knot is relatively circular with out any distortions. The pictures were taken by the microscope imaging system in the splicing machine in which we pull the fiber to obtain the small micro-knot.

After tying the micro-knots we returned them into the tapering machine which is based on CO\textsubscript{2} laser heating source. In the tapering machine we were able to accurately oriented the micro-knot into the CO\textsubscript{2} laser heating beam and
Figure 1. Representative transmission spectrum of the micro-knot. These results present a free-spectral range of 1.2 nm and an amplitude spectral oscillations of 7 dB.

Figure 2. Microscope images of the micro-knot from two orthogonal directions. The picture shows a clear image of the micro-knot. The micro-knot is relatively circular with out any distortions.
to direct the laser beam so it will heat the overlapping reign in the knot. This reign is where there is coupling between the tapered fiber. By heating this reign, we increase the coupling strength between the fibers which influence the Q-factor of the micro-knot resonator.

Next, we measured the spectral oscillation amplitude as a function of the fusing energy which corresponds to the coupling strength in the micro-knot. The spectral oscillation amplitude is related to the micro-knot efficiency and by maximizing the efficiency, we satisfies the critical coupling conditions. The results are presented in Fig. 3 together with two pictures of the micro-knot before the fusing (left) and after 0.6 J fusing energy (right). As evident, as we increase the fusing energy the coupling strength increases which influence the spectral oscillation amplitude. The critical coupling conditions are obtained at 0.13 J and increasing the fusing energy and the coupling strength further reduces the micro-knot efficiency. After reaching a minimum at 0.4 J the efficiency starts to increase again but due to the high energy levels, the shape of the micro-knot was distorted as seen in the right inset and the signal dropped below the noise level.

![Figure 3. Amplitude of spectral oscillations as a function of the energy delivered into the knot during fusing. Left inset presents picture of the knot before the fusing. Right inset presents the distorted knot after 0.6 J was delivered into the knot.](image)

We also measured the birefringence of the fused fiber, the coupling efficiency and the free-spectral range of the cavity as a function of the fusing energy. These measurements are published by Shahal et al.\textsuperscript{4–6} We repeated the measurements for different types of fiber micro-knots such as eight-figure and double micro-knots as presented in Fig. 4. All the results reveal that the fused micro-knots are superior over regular micro-knots and are very simple to fabricate.

We measured both the transmission and the reflection spectra of the eight-figure micro-knot. The measured spectra are presented in Fig. 5. The reflection spectra is higher due to the shape of the micro-knot which mainly direct the light forward and just a small fraction is oriented backward. The free-spectral range of both the reflection and the transmission is similar but with a $\pi$ phase shift which is also explained by the shape of the micro-knot.
Figure 4. Examples of special fiber micro-knot. Left: double knot. Right: eight-figure knot. The pictures were taken with a microscope imaging system in the splicer machine. All the results reveal that the fused micro-knots are superior over regular micro-knots and are very simple to fabricate.

Figure 5. Transmission and reflection spectra of an eight-figure micro-knot. The reflection spectra is higher due to the shape of the micro-knot which mainly direct the light forward and just a small fraction is oriented backward. The free-spectral range of both the reflection and the transmission is similar but with a $\pi$ phase shift which is also explained by the shape of the micro-knot.
We also utilized these fiber micro-knot to detect different materials by measuring the spectral response.\textsuperscript{7–9} We measured the spectral response of the fiber micro-knot when submerged into water and ethanol and comparing the spectra to the transmission spectrum of micro-knot in air. The results are presented in Fig 6. As evident, a clear difference is presented in the spectrum which indicates that it is possible to distinguish between these different materials by measuring the fiber micro-knot spectrum.

![Figure 6. Transmission spectrum of the micro-knot when submerged in different liquids. The difference in the spectra indicate that it is possible to detect different materials based on the transmission spectrum of the micro-knot. A clear difference is presented in the spectrum which indicates that it is possible to distinguish between these different materials by measuring the fiber micro-knot spectrum.](image)

Another advantage of fusing the micro-knots is high robustness to stresses. Therefore, we fabricated an eight-figure micro-knot and rotate one end compare to the other end which result in twisting the knot. This method of twisting the knot changed the coupling of the knot and enables accurate fine-tuning of the micro-knot parameters after fusing. We note that previous experiments on fusing of large fiber knots were reported but only for large knots and without investigating the knot robustness, birefringence, and coupling strength.\textsuperscript{3} The results reveal that fused micro-knots are more than 10 times stronger than un-fused micro-knots.\textsuperscript{6}

We note that the Q-factor and the finesse of the micro-knot before fusing are lower than previously published. This is due to the relative large diameter of the tapered fiber which is limited to 3 $\mu$m by our CO\textsubscript{2} tapering machine. We are investigating now several methods for reducing the tapered fiber diameter bellow 1 $\mu$m which will increase the resonance deep and the finesse of the micro-knot fiber. Nevertheless, our results prove that fusing the micro-knot increases the coupling strength the robustness and the stability and can tune the resonance wavelength.

3. CONCLUSIONS

To conclude, we presented that fused fiber micro-knots are superior over regular micro-knots. We investigate the coupling strength, birefringence, Q-factor, and spectral response of fused micro-knots and obtain results which indicate that such micro-knots can improve devices that are based on fiber micro-knots.
We also investigated fiber micro-knots with higher complexity and observed that fused complex micro-knots have superior properties over un-fused micro-knots including higher stability and robustness.

All the experimental results, methods and theoretical calculations are presented in details by Shahal et al.\textsuperscript{4-6} This research was supported by the Ministry of Science, Technology and Space, Israel.

REFERENCES


