EMBEDDED SENSORS BASED ON NOVEL MICROWAVE GRATING

ABSTRACT
This paper reports a coaxial cable Bragg grating constructed by crimping the cable at periodic distances. Two types of crimping methods are explored. The effects of varying the number of deformations per cable are also explored. Resonances were found in both the transmissions and reflection spectra, indicating successful Bragg grating.

1. INTRODUCTION
In recent years, the condition of civil structures such as bridges, dams and buildings has been questioned. This has exposed the need for better monitoring methods of these structures. One method being developed for structural health monitoring (SHM) uses embedded sensors. These sensors are embedded while the structure is being built, not attached afterwards. There are various parameters SHM sensors could be used to monitor such as temperature, pressure, strain and vibration. Each sensor must be able to survive and operate at high temperatures, withstand high pressure or strain, have a large dynamic range, be highly sensitive and be embeddable. Fiber optic cable has been used extensively as sensors for many SHM parameters such as strain temperature, pressure and vibration. However, due to the fragile nature of fiber optic cable, along with the limited range in materials, fiber optic cable is not an ideal candidate for structural health monitoring.

An alternative to fiber optic cable is coaxial cable. Coaxial cable has many advantages over fiber optic cable in terms of SHM. Coaxial cables can withstand high temperatures, are robust, have a large dynamic range and are available in a wide range of materials. Compared to fiber optic, they are inexpensive because the excitation, probing and processing is all in electrical form. Because of these advantages, the possibility of applying fiber optic concepts to coaxial cable has been explored. Munday et al. alternated 50Ω and 93Ω coaxial cable segments to create a coaxial cable photonic crystal. A fiber optic concept, Bragg grating, could be applied to coaxial cables. Bragg grating is created by periodic impedance changes in the cable. At each impedance change the electromagnetic (EM) wave is partially reflected. The transmitted portion of the EM wave travels until it reaches the next impedance discontinuity. The EM wave is again partially reflected. Resonances in both the transmission and reflection spectra are generated by the superposition of all in-phase reflections. A fundamental frequency is determined by the Bragg condition.

Wei et al. reported fabrication of a coaxial cable Bragg grating (CCBG). The CCBG was created by drilling holes through the outer conductor and the dielectric. The inner conductor was not disturbed. A spacing of 6.4cm was kept between each hole. The device had a fundamental frequency of 1.56GHz. In Fig.1 the transmission and reflection spectra, before and after the holes were drilled, is shown.

The blue lines are before any holes are drilled and the red lines are after 23 holes were drilled. In the transmission spectrum it can be seen that the drilling did not add loss to the system, as the lines overlap except at the fundamental frequency and the resonances. There are some disadvantages when using the drilling method. Before drilling, part of the outer jacket is removed. Also, the drilling removes part of the outer conductor and the dielectric. Contaminates can interact with the cable, possibly degrading or eroding the material. This along with physical removal of cable material can result in structural weakness or lower signal integrity of the cable. To overcome these problems a new method for creating impedance discontinuities must be explored. One possible method is crimping, where the cable is deformed creating the impedance discontinuity. This paper reports the results of a coaxial cable Bragg grating (CCBG) using the crimping method.

2. PROCEDURE
In the works reported by this paper a SubMiniature version A (SMA) type coaxial cable was used. The cable was constructed of an inner conductor of solid copper with a diameter of 0.812mm, a dielectric layer comprised of solid polyethylene with a diameter of 2.95mm, an outer conductor made of copper braid and a plastic jacket with diameter 4.95mm. The cables were deformed using a crimping tool. The deformations were created by crimping the cable at periodic distances. Two types of deformations were tested in this experiment. The first deformation, called method 1, used a small hexagonal slot in the crimper. Method 2 used a slot with a protrusion, creating an indent on one side of the cable. In addition to testing various crimping methods, a variety in the number of
deformations per cable was also tested. Two cables had 30 deformations and the remaining two cables had 15 deformations.

The transmission and reflection spectra of the CCBGs were acquired using a vector network analyzer. The reflection spectrum was determined by measuring $S_21$ and the transmission spectrum was determined by measuring $S_{11}$. Using a MATLAB script, the losses were scanned from 100kHz to 6GHz, using a total number of 1601 scanning points. Both the transmission and reflection spectra were recorded before and after the deformations were made. These were compared to see if any additional loss was introduced into the system by the deformations. Any fundamental frequencies and higher resonances are labeled on the plots. The transmission and reflection spectra of Cables 2-5 can be seen in Fig. 2 through Fig. 5.

3. RESULTS

The transmission and reflection spectra in Fig 2 through Fig. 5 tell us the quality of each CCBG. Cable 2, which has 15 deformations created by crimping method 2, contains three major spikes in the reflection spectrum. The fundamental frequency is at 1.6414GHz. The first harmonic is at 3.3745GHz. The last peak is at 4.9786GHz. The difference in frequency between the first and seconds peaks is 1.6041GHz. This is a 2% difference from the fundamental frequency. The differences in frequency between the second and third peaks is 1.6819GHz. This is a 2% difference from the fundamental frequency. The peaks are not very well defined. All three peaks have a second peak very close to them. This makes it difficult to calculate the exact frequency of each resonance. The transmission spectrum has the frequencies corresponding to the peaks in the reflection spectrum marked on it. There are no notches in the transmission spectrum that can be attributed to the Bragg grating. However the background noise for the cable before and after the deformations were made are almost exact from 100kHz to 3GHz. From 3GHz to 4.66 GHz the cable with the deformations has less noise. After 4.66GHz the deformations add to the loss of the system.

Using the same crimping method as Cable 2, Cable 3 was created with a total of 30 deformations. The spectra of Cable 3 can be seen in Fig. 3. There are notches visible in the transmission spectrum and corresponding peaks visible in the reflection spectrum. The fundamental frequency in the reflection spectrum is 1.6672GHz. The first resonance is at 3.3229GHz and the second resonance is at 4.9786GHz. The difference between the fundamental and first harmonic is 1.6557GHz. This is less than a 1% difference from the fundamental frequency. The difference in frequency between the first and second resonances is also 1.6557GHz. The space between all three peaks is the same. These peaks are more defined than those of Fig. 2. The fundamental and resonance frequencies are different in the transmission spectrum in Fig 3. The fundamental frequency is 1.6819GHz. The first resonance is at 3.3266GHz and the second resonance is at 4.9859GHz. This results in a difference of 1.6447GHz between the fundamental and first resonance and a 1.6593GHz between the first and second resonances. These correspond to a 2.2% and 1.3% difference from the fundamental frequency respectively. The notches in the transmission spectrum are very well defined in Fig. 3. When the background noise of the cable before and after the deformations is compared, there is no visible noise added to the system from the deformations. The notches and the peaks the Fig. 3 are clearly proportional to the frequency.

The deformations in Cables 4 and 5 were created using crimping method 1. The deformations were not as large in this method. The spectra for Cable 5 can be seen in Fig. 4. Cable 5 used 15 deformations to create the CCBG. The fundamental frequency is 1.6893GHz. The first resonance is at 3.3413GHz and the second resonance is at 4.9970GHz. These values result in a 2.2% and 2.0% difference from the fundamental frequency. The peaks at the fundamental and resonance frequencies are barely discernible from the
background noise. The second resonance is clearly defined with no other peaks close to it. When the same frequencies are examined on the transmission spectrum the only reliable notch is near the second resonance at 4.9933GHz. There are no visible fundamental or first harmonic notches.

Figure 4: Reflection and transmission spectra of Cable 5 (15 deformations, crimping method 1)

Figure 5 shows the spectra for Cable 4, where 30 deformations using method 1 were used. The fundamental frequency is 1.6746GHz. The first resonance is at 3.3339GHz and the second resonance is at 4.9823GHz. Using these values we obtain a 0.9% difference and 1.6% difference respectively. The first resonance is clearly defined with no peaks near it. The fundamental and second resonances are not as neatly defined. Both of these peaks have a second peak near the same frequency. There are no definite notches in the transmission spectrum due to Bragg grating. When the spectrum is observed at the frequencies determined from the reflection, a small notch is seen at 3.339GHz. However, due to the level of background noise, it is difficult to determine if this is caused by the Bragg grating or not. The level of background for both transmission and reflection spectra seem to be unaffected by the deformations.

Figure 5: Reflection and transmission spectra of Cable 4 (30 deformations, crimping method 1)

8. CONCLUSION
Analysis of the spectra for the different cables will help determine the result of the different crimping methods and impact of the various total number of deformations. Figure 3 has the best defined peaks in the reflection spectrum and notches in the transmission spectrum. Figure 4 has very poorly defined peaks in the reflection spectrum and notches in the transmission spectrum. The quality of spectra in Fig. 2 and Fig. 5 are about the same. Based on these results the crimping method 2 is the better method. The number of deformations also affects the quality of the CCBG. Further study should be done to determine the impact of the total number of deformation per cable to include more than just 15 and 30 deformations.

In most of the spectra, spacing between resonances was not exactly uniform. The space between two adjacent notches or peaks should be equal to the fundamental frequency. The spacing was with 6% for all cables and within 2.2% for most of the cables. The peaks or notches in the spectra should be well defined. In Fig. 3 this occurs. In the remaining figures the peaks widen, usually caused by a second peak close to the primary peak. In order to improve the quality of each peak and notch, as well as the spacing between them, the spacing between each deformation must be improved. Special steps should be taken to make sure each deformation is uniform made and evenly spaced.

This work reports a coaxial cable Bragg grating created by crimping. Two crimping methods were investigated along with the effects of various numbers of total deformations per cable. Crimping method 2, with the protrusion on one side, worked best. Expanding on this progress better crimping methods may be developed. This new method for creating coaxial cable Bragg gratings will allow the use SHM sensors, without the contamination and erosion problems associated with the drilling method.
8. ACKNOWLEDGMENTS
I would like to thank Dr. Hai Xiao for his advising on this work and Tao Wei for his help with the MATLAB code used in this experiment. I would also like to thank the Intelligent Systems Center for its support of this work.

9. REFERENCES