Biomimicry in Microwave Photonics and Soft Robotic with Fiber Optics Sensors

Mable Fok
Lightwave and Microwave Photonics Laboratory, College of Engineering, University of Georgia,
Athens, GA 30602, USA
mfok@uga.edu

Qidi Liu
Lightwave and Microwave Photonics Laboratory, College of Engineering, University of Georgia
Athens, GA 30602, USA
qidi.liu@uga.edu

Mei Yang
Lightwave and Microwave Photonics Laboratory, College of Engineering, University of Georgia
Athens, GA 30602, USA
meiyang@uga.edu

***Abstract*— Biomimicry offers effective solutions to critical challenges in our society by learning and mimicking the strategies used by living organisms. In this paper, biomimicry in microwave photonics and soft robotics will be introduced. Bio-inspired approaches has been used to provide promising solutions to the field of microwave photonic such as localization, jamming avoidance, and steganography. The analog solution provided by bio-inspired approaches does not propose a bandwidth limitation because there is no need for digitization. In recent years, soft robotics has been a promising alternative to conventional robots by offering safer robot-to-human interaction. Unique embedding configurations allow fiber optic sensor to be used in soft robotic to provide feedback for precise control. The second part of this paper will introduce several bio-inspired soft robots with embedded fiber optic sensors. Fiber optics provide flexible and light weight sensing solution, making it a promising candidate for sensing in soft robotics.**

Keywords—biomimicry, bio-inspired, microwave photonics, soft robotics, fiber optic sensing

I. Introduction

Living organism has undergone billions of years of evolution that results in effective biological algorithms and strategies to ensure their survival and reproduction. They have evolved to adapt to their living environment, to communicate effectively, to conceal their appearance from predators and prey, and to sense their surrounding for danger and navigation. On the contrast, human technologies have a short history and have been facing critical challenges in many aspects such as security and availability of communication channels, as well as the safety for human–robot interaction. By understanding biological strategies in living organism, we could get inspired by the nature and explore effective solutions for overcoming critical challenges in human technologies.

In this paper, our recent biomimetic research progress in (i) microwave photonics and (ii) fiber-optic sensor embedded soft robotics will be introduced through four projects. First, we learned from marine hatchetfish to conceal their appearance from both predators and preys using camouflage strategies, and apply the strategies for steganography in radio over fiber transmission. Next, we will discuss how jamming avoidance response in Eigenmannia inspires an effective solution for inadvertent jamming in radar systems. Then, we got inspiration from twining plants that has a strong spiral grip for making a spiral gripper to hold elongated objects. Just like the twining plant, the soft robotic gripper has a fiber optic sensor that can sense the target object for a secure grip. Furthermore, a soft robotic vertical climber with fiber optic sensors has been designed based on the motion of an inchworm for effective climbing on glass wall.

II. Biomimicry in Microwave Photonics

Research in the field of neuromorphic and bio-inspired photonics has drawn significant interest over the last decade. Neuromorphic photonics research including the design of a spiking photonic neuron [1], performing task such as pattern recognition [2], and the development of photonic neural network [3], to name a few. Meanwhile, biological algorithms are examined and have inspired a number of microwave photonic signal processing tasks including angle of arrival measurement, 3D localization [4], and jamming avoidance [5], and stealth transmission [6].

A. Marine Hatchetfish Camouflage Strategies for Self-Destructive Steganography in Radio Over Fiber System

When discussing vulnerability of a transmission, wireless network usually draws the most concern due to its broadcast nature. However, fiber optic network is not completely immune to interception because it is not hard to tap into an optical fiber to access the transmission. Radio-over-fiber network is essential for supporting high-speed transmission. To minimize vulnerability in the physical fiber optics network, effective cryptography is needed to secure the sensitive information. Effective cryptography requires both encryption and steganography to scramble and hide the sensitive signal in plain sight. Although, most research has been focusing on encryption techniques, but cryptography cannot be completed without steganography.

Marine hatchetfish has two underwater camouflage strategies that conceal their presence from predators and preys, referring to silvering and counterillumination. Silvering is achieved through constructive and destructive interference at the microstructured skin of the marine hatchetfish, such that the fish is invisible from the side. Counterillumination is performed by the fish by illuminating the bottom of the fish to the same brightness and color as the surrounding, such that the fish will not have a dark shadow when seen from the bottom.

The above camouflage strategies are highly desired in a communication system. Inspired by the marine hatchetfish, a RF steganography technique is developed that uses interference to self-destroy a signal when the attacker attempts to intercept the transmission [6]. The advantage of using interference for steganography is that the attacker will not be able to get a hold of the sensitive signal when intercepted, which has been the challenge in most conventional steganography approaches.

In our experiment, photonic based finite impulse response is used to achieve silvering, and a wideband optical comb carrier is used to achieve counterillumination. Self-destructive steganography has been experimentally demonstrated

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successfully as shown in Fig. 1. If the attacker attempts to intercept the transmission, the attacker will experience transmittance of the steganography system as shown by the blue curves in Fig. 1(a). The constructive points are at the peaks up around 12.5 GHz, while the sensitive signal is at 5 GHz and is currently under destructive interference. Therefore, the sensitive signal will be self-destroyed by the system at the moment when the attacker is intercepting it.

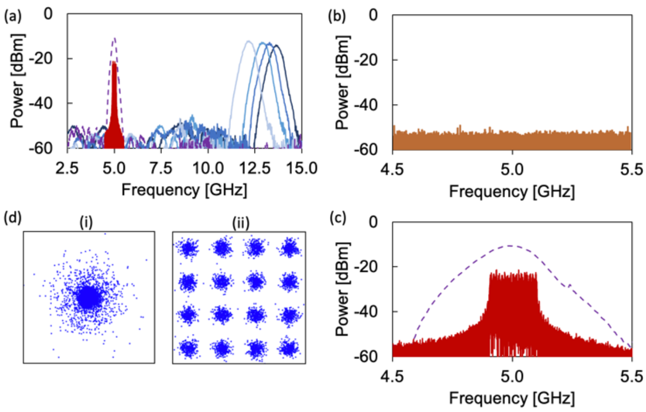

Fig. 1: (a) Transmittance of the channel as seen by the attacker (blue) and legitimate receiver (purple); (b) Sensitive signal is destructively interfered at the attacker's hand; (c) Sensitive signal is received successfully at the designated receiver; (d) Constellation diagrams seen by (i) the attacker (ii) legitimate receiver.

The RF spectrum of the received signal during self-destruction is shown in Fig. 1(b) and the constellation diagram is shown in Fig. 1(d)i. On the other hand, if the legitimate user is receiving the signal at the designated location, the receiver will experience constructive interference at the sensitive signal frequency as shown by the purple dashed curve in Fig. 1(a) and (c), as a result the sensitive signal can be clearly seen as shown in red. A clear constellation diagram is also resulted (Fig. 1(d)ii). Just like the marine hatchetfish, the steganography system uses interference to ensure the attacker will not get a hold of the sensitive signal, and the optical carrier has the same intensity and color as the background noise.

B. *Jamming Avoidance Response in Eigenmannia for Mitigating Inadvertent Jamming in Radar Systems*

While wireless microwave technology offers us the conveniency of having anytime anywhere service, however, the broadcast nature of wireless system making it prone to various types of jamming. Inadvertent jamming has always been overlooked because the jamming source is usually friendly. However, inadvertent jamming has the same effect as intentional jamming – resulting in disruption of existing wireless communications.

Eigenmannia is a gene of electric fish that uses electric field to navigate, interact with other electric fish, and to sense their surroundings. The Eigenmannia has a powerful jamming avoidance response (JAR) that mitigate frequency jamming from a nearby fish. The principle of JAR is based on the unique relationship between phase and amplitude when interacting with frequency that is higher or lower than the fish's electric field frequency. By analyzing the amplitude and phase information between the jamming electric field and the fish's own electric field, the Eigenmannia can intelligently know whether they need to maintain, increase, or decrease their electric field frequency to avoid jamming.

We examine how Eigenmannia performs JAR and use photonics to reassemble the four functional blocks for performing jamming avoidance. First, the zero-crossing point detection unit is built based on self-phase modulation in a semiconductor optical amplifier (SOA). Then, the zero-crossing output and the beat signal is launched to the phase unit for comparing the phase between the two signals using cross-gain modulation in SOA. Next, the envelope of the beat signal will undergo an inversion and delay in the amplitude unit to distinguish the rising and falling envelopes. Lastly, the phase and amplitude information from the above units will be launched to the Arduino based logic unit for frequency adjustment if needed.

By implementing the JAR using photonics, a successful automatic jamming avoidance has been achieved experimentally. Fig. 2 shows the automatic adjustment of frequency for single tone and analog amplitude modulated signals between MHz to GHz range. Channel availability can be ensured using JAR to mitigate inadvertent jamming.

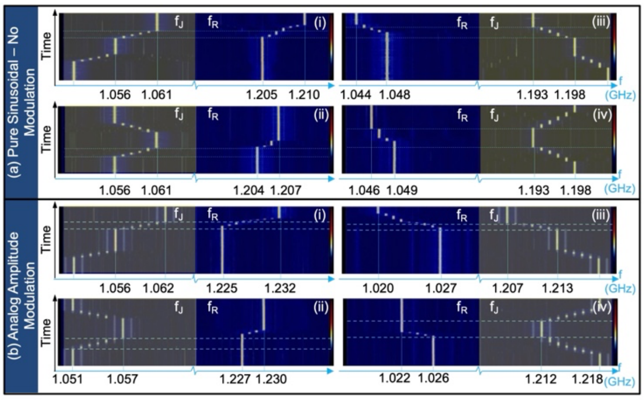

Fig. 2: Spectral waterfall of the Eigenmannia inspired photonic based jamming avoidance response. Yellow shade: jammer moving in different spectral direction. (a) single tone jamming and reference signals; (b) analog modulation for both jamming and reference signals.

It is worth to notice that no manual adjustment is needed to enable automatic jamming avoidance. The Eigenmannia inspired jamming avoidance response shows that as the jammer frequency is approaching the jamming frequency limit, the system would automatically enable and detect if the jamming frequency is higher or lower by analyzing the amplitude and phase information. The jamming avoidance system would not chase after the jammer just for maintaining the frequency different, instead, the frequency would be maintained if no jammer is spectrally close enough to trigger the response.

III. Biomimicry in Fiber Optic Sensor Embedded Soft Robotics

Soft robots have shown promising properties to complement conventional rigid robots. Due to the soft and flexible nature of soft robots, a lot of the soft robotic designs are inspired by invertebrates or plants. For example, gripper that reassemble an octopus tentacle [7], crawler move like a snake or worm [8], as well as swimming robot that is inspired by falling leaves [9]. However, most soft robots do not have sensors to provide feedback and for sensing their surroundings because it is challenging to embed electronic sensors in a soft robot without hindering the movement.

A. *Twining Plant Inspired Sprial Gripper*

Soft robotic grippers have been one of the most popular soft robots to develop because it is an essential tool in various applications including manufacturing automation and biomedical engineering. However, most soft robotic grippers mimic human hand with fingers, which requires a large operation space and is not good at gripping elongated objects.

By observing our nature, we drawn inspiration from twining plants. Due to the growth hormones in twining plant, a directional growth movement is resulted depending on its interaction with its surroundings. The growth rate on the side of the tendrils that touches an object is slower than the side that is not touching, resulting in a spiral movement. The spiral motion results in multiple discrete points of contacts as the anchorage points to provide a secure grip – think about those tiny tendrils that can support the weight of a watermelon.

With the inspiration from twining plants, a pneumatic soft robotic spiral gripper is designed and experimentally demonstrated [10]. The design of the spiral gripper is shown in Fig. 3(a), that has a fiber optic sensor made of high birefringence fiber in the core of the gripper for sensing the grip and external perturbation. The sensor is embedded in an elastic core to prevent delamination and ensure repeatability of the measurement. A spiral air channel is used to mimic the directional growth movement around the target, as shown in Fig. 3(b). The fiber optic sensor is capable of distinguish the target object diameter, the number of spiral turns, as well as detecting external perturbation as shown in Fig. 3(c).

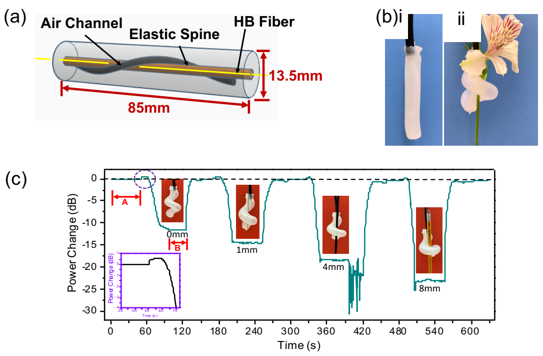

Fig. 3: (a) Detail design of the twining plant inspired soft robotic spiral gripper; (b)i. Soft spiral gripper before actuation; ii. Spiral gripper after actuation; (c) Real-time monitoring of the twining plant inspired spiral gripper using optical power measurement.

B. *Inchworm Inspired Vertical Climber*

Vertical climbing is one of the hardest forms of locomotion due to gravitational effect on the vertical climber which require both upward motion and good adhesion to the climbing surface. In fact, a lot of good climbers can be found from our nature such as geckos, spiders, and worms. One important feature of vertical climber is the ability to tell if they are securely hanging on the wall, i.e. if the intended motion is successful or not to prevent falling. Furthermore, due to the boneless nature of soft robots and the effect of gravitational force, soft robotic motions become uncertain and have low precision. Therefore, it is important to have an embedded sensor inside the soft robotic vertical climber to provide feedback and climbing information, such that any undesired motions could be corrected at early stage to prevent falling.

We draw inspiration from the inchworm climbing motion and designed a vertical soft robotic climber [11]. Inchworm only have two pairs of legs – one in the front and one at the back, but it is an effective climber compare with caterpillar because of its unique climbing motion. Inchworm draws its hind end forward while holding on to the wall with the front legs, then it advances its front section while holding on with its back legs. The soft robotic climber is illustrated in Fig. 4(a). Three fiber Bragg grating (FBG) sensors are embedded in each section of the body to monitor the climbing motion, and the results are shown in Fig. 4(b). Fig. 4(c) shows the series of motion of the soft robotic climber to move upward.

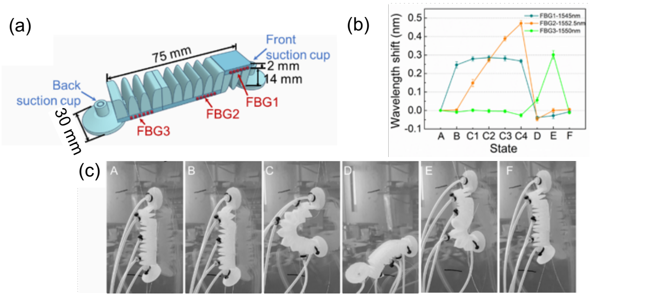

Fig. 4: (a) Inchworm-inspired soft robotic climber design; (b) Measured wavelength shift of the three FBGs at different states with respect to state A; (c) Step by step motion of the robot climbing up a 90º vertical glass wall.

IV. Summary

By learning from the nature, effective solutions can be inspired for solving critical challenges in the field of microwave photonics and soft robotics. This paper introduced some of our recent progress on biomimicry in photonics to improve security of our communication systems and to ensure a safe robot-to-human interaction. There are a lot of treasure in the nature for us to explore and learn from, which could be translate to a solution to improve human technologies.

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