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USE OF TAPERED OPTICAL FIBER AS A HEART RHYTHM SENSOR (ARRHYTHMIA)

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Abstract-Early detection of cardiac arrhythmias is crucial in preventing serious cardiovascular complications such as stroke and heart failure. Conventional methods such as electrocardiography (ECG) and Holter monitoring have limitations in terms of portability, sensitivity to noise, and dependence on electrodes in direct skin contact. This study explores the potential of using tapered fiber optics as a non-invasive optical sensor to detect cardiac physiological signals related to arrhythmias. Tapered fibers have high sensitivity to refractive index changes and microscopic vibrations, which can be utilized to detect cardiac electromechanical activity in real time.
This study shows that tapered optical fibers have significant potential as alternative sensors in more portable and high-precision cardiac monitoring systems. Further development can be directed to wearable device applications and integration with Internet of Medical Things (IoMT) systems for continuous and remote patient monitoring.

Keywords:*Tapered fiber optic, Optical sensor, Cardiac arrhythmia, Biosensor, Medical optics, Heart detection.*

1 Introduction

Physics is a basic science that plays an important role in explaining various natural phenomena, both macroscopic and microscopic. In the field of medicine and health technology, physics makes significant contributions, especially through the branches of optics, mechanics, and electromagnetics. The concepts of physics are not only used to understand the function of the human body, but also to design and develop detection devices and monitoring systems for various physiological parameters precisely and in real time. One important application of physics in the medical field is the use of light waves and optical fibers in sensory systems. Optical fiber is a light transmission medium that works based on the principle of total reflection in the fiber core. However, when the fiber structure is modified—for example by tapering its cross-section (tapered fiber)—some of the light exits the core and interacts with the external environment through the evanescent field. This phenomenon is used to detect physical or chemical changes in the environment around the fiber, making it a very sensitive and adaptive sensor to various biological parameters.(Méndez, A., & Morse 2011)

Tapered fiber optics have a diameter that is gradually reduced at a certain point. This change causes most of the light to propagate close to the surface of the fiber, so that it can respond to changes in refractive index, temperature, pressure, and vibrations that occur around it. This advantage makes it very potential for use in the biomedical field, including as a heart rate sensor and arrhythmia detector, because it is able to detect very small mechanical signals, such as the movement of blood vessel walls due to heartbeats.(Zhou, H., Zhang, Y., Hu, Y., & Peng 2020). On the other hand, cardiac arrhythmia is a condition of abnormal heart rhythm caused by disturbances in the electrical impulses that regulate the heartbeat. Arrhythmia can cause the heartbeat to be too fast (tachycardia), too slow (bradycardia), or irregular.

This condition not only causes mild symptoms such as dizziness and fatigue, but can also lead to serious complications such as stroke, heart failure, and sudden death if not detected early.(Clinic 2021).

Current arrhythmia detection is generally done using an electrocardiogram (ECG) that records the electrical activity of the heart through electrodes on the skin surface. Although this method is quite accurate, it has limitations in terms of portability, long-term comfort, and sensitivity to environmental disturbances. Therefore, an alternative cardiac monitoring system is needed that is non-invasive, portable, sensitive, and free from electromagnetic interference, this is where tapered fiber optics have the potential to be an innovative solution. Various studies have shown that tapered fiber-based sensors can detect heart rate continuously by detecting mechanical signals generated by blood flow. This signal is then converted into an optical signal, which can be analyzed to recognize normal pulse patterns and detect heart rhythm disorders.(Zhou, H., Zhang, Y., Hu, Y., & Peng 2020). Additionally, because it is optically based, the system is not affected by electromagnetic fields, making it ideal for use in modern hospital environments filled with electronic devices.

This approach also opens up the possibility for integration into wearable devices such as smart watches or health bracelets, allowing real-time monitoring of arrhythmias outside the hospital. Thus, the use of tapered optical vibrations is not only an alternative medical detection tool, but also plays a role in driving the development of e-health and telemedicine systems in the future.

This article will review in depth the working principle of tapered optical fiber in the context of optical physics, its characteristics as a biomedical sensor, and its potential in detecting arrhythmia efficiently and accurately. In addition, it will discuss the technical challenges, advantages over conventional technologies, and future development directions in the context of integration with modern health monitoring systems.

2 Methodology

This study uses a literature study approach (library research) as the main method in exploring, analyzing, and synthesizing relevant information regarding the use of tapered optical fiber as a sensor to detect heart rhythm disorders or arrhythmias. This method was chosen because it is able to provide a strong theoretical understanding of the working principles, potential applications, and advantages of technology and optics in the medical world, especially in the field of cardiology.

The first step in this research is collecting literature data from various trusted scientific sources. The literature is collected through systematic searches in various databases such as Google Scholar. From this search, journals and scientific articles relevant to the research topic are obtained.

The next stage is the analysis of the literature obtained. The analysis is carried out qualitatively with descriptive-analytical methods to identify and evaluate the concepts, methods, and results presented by previous researchers.(Mishra, S.K., Mishra, R., & Gupta 2019)explained that tapered optical fiber has a high capability in increasing detection sensitivity because its geometry changes allow light to interact more with the external environment through evanescent mode. This makes this technology very potential to be applied as a biomedical sensor, including in detecting heart activity.

Furthermore,(Wang, Y., Liu, B., & Huang 2021)shows that the use of fiber optic sensors is able to detect heart signals in real time with high precision. This sensor can capture fluctuations in heart rate signals accurately, which is important in detecting rhythm disturbances or arrhythmias. This is reinforced by research(Zhang, Y., Hu, Y., Peng, W., & Zhou 2020)which states that by tapering the optical fiber, the sensitivity of the sensor increases due to the expansion of the optical interaction area with external parameters such as pulse rate and blood pressure.

Study(Rahman, MM, & Chowdhury 2018)also supports that fiber optics can be integrated into wearable devices to continuously monitor heart health. This system is able to provide early warning of any irregularities in heart rhythm, making it highly relevant for use in monitoring patients at risk of arrhythmia. In addition,(Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M., & Ayyash 2017)In his study on

Internet of Things (IoT) technology, he stated that the integration of fiber optic sensors with IoT-based communication systems can increase efficiency and speed in the process of detecting and responding medically to heart disorders.

The results of the synthesis of all the literature are used to formulate a conceptual basis for the design and function of a tapered fiber optic sensor system in arrhythmia detection. By comparing various approaches and previous research results, this study aims to contribute to the development of more sensitive, precise, and non-invasive early detection tools based on fiber optic technology.

3 Discussion

Arrhythmia is a condition that affects the rate or pattern of your heart beat. When you have an arrhythmia, your heart may beat too fast, too slow, or in an irregular pattern. An excessive heart rate is called tachycardia. A slower heart rate is called bradycardia. Most arrhythmias are harmless, but some can be serious or life-threatening. In the case of an arrhythmia, your heart may not be able to pump enough blood throughout your body. This lack of blood supply can damage your brain, heart, and other organs.

Arrhythmia is defined as a heart pattern that does not follow the normal sinus rhythm. This can occur due to disturbances in impulse formation, impulse delivery, or a combination of both, and can be dangerous because it can reduce cardiac output, blood flow to the heart muscle, or even trigger more severe arrhythmia conditions. Although the term 'dysrhythmia' seems more appropriate to describe an abnormal heart rhythm (because the term arrhythmia indicates the presence of a rhythm), the term 'arrhythmia' will be used in this discussion because it has now become a widely accepted medical term (Andika, GA, Sukohar, A., and Yonata 2021).

The use of tapered optical fiber as a biomedical sensor shows great potential in detecting cardiac arrhythmias in real time. Based on the literature review conducted, several studies have shown that tapered fiber-based sensors are able to respond to the slightest mechanical fluctuations produced by blood flow or pulse. This technology works by converting mechanical disturbances into changes in light intensity which are then interpreted as optical signals.

For example, research by(Wang, Q., Zhang, Y., Chen, G., Chen, Z., Hee 2021)demonstrated that heart rate signals can be captured with high sensitivity using this sensor, even without requiring direct invasive contact with body organs. Tapered fiber optic sensors are used in a variety of applications such as environmental monitoring, healthcare, and structural health monitoring.(Edwards, PS; Janisch, CT; He, L.; Zhu, J.; Yang, L.; Liu 2012) (Brambilla 2010) (Lee, B.; Roh, S.; Park 2009)(Leung, A.; Shankar, P.M.; Mutharasan 2007)(Vahala 2003)(Kieu, KQ; Mansuripur 2006).

Furthermore, this technology is ideal for combination with wearable devices. The sensor can be incorporated into a bracelet or watch structure, allowing continuous and portable monitoring of heart rhythm. This concept is relevant to the development of e-health and IoT-based remote monitoring systems, as conveyed by(Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M., & Ayyash 2017).

However, technical challenges remain to be overcome, such as long-term signal stability, the effects of body movement, and the integration of optical systems with digital electronic components. These challenges are the focus of future device development, including efforts to automatically calibrate signals and AI-based data processing.

Overall, tapered fiber optics offers key advantages such as:

1. High level of sensitivity through evanescent field effect.
2. Resistance to electromagnetic interference.
3. Potential for miniaturization and integration in portable devices.

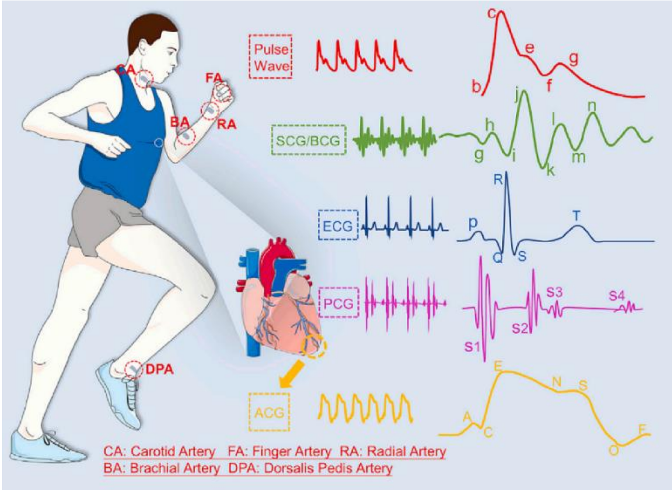


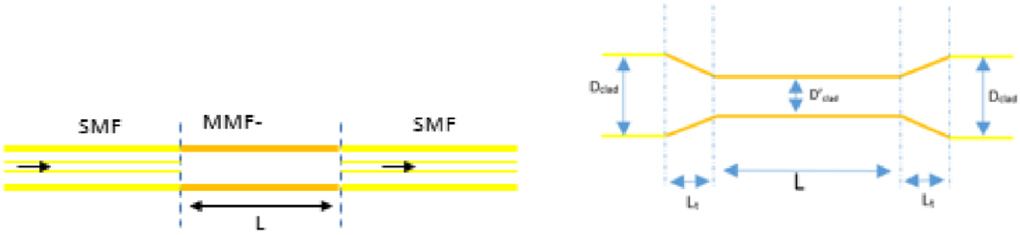
Figure 1: Five methods of monitoring heart activity

In general, HR and signs related to cardiac activity can be obtained in the following five ways: ballistocardiograph (BCG), electro-cardiograph (ECG), pulse wave (PW), phonocardiogram (PCG), and apex cardiogram (ACG), which are shown in Figure 1.(Lin, J., Fu, R., Zhong, X., Yu, P., Tan, G., Li, W., Zhang, H., Li, Y., Zhou, L., Ning 2021)

BCG is a type of micro vibration caused by human heart activity. It is a non-invasive signal, which can be collected by detecting mechanical signals from the patient's physical contact platform. When the heart pumps blood, the blood will hit the blood vessels, producing a force opposite to the blood flow, which is then transmitted to the body surface.(Gordon 1877). By analyzing the BCG signal, the health of the cardiovascular system and the synchronous information of cardiac hemodynamics can be reflected. ECG obtains cardiac activity by measuring the bioelectrical information of the heart.(Asif, IM, Drezner 2016). When the heart contracts, it produces a small electrical pulse, which spreads through the myocardium. An ECG can be obtained by monitoring this bioelectrical pulse. The method of measuring PW is to roughly estimate HR by detecting the pulse time of large arteries, such as the radial artery and carotid artery. In general, HR can be estimated from the pulse rate.(Boutouyrie, P., Bussy, C., Lacolley, P., Girerd, X., Laloux, B., Laurent 1999).

This method is simple and practical, but if the patient has arrhythmia, the measured pulse rate will be different from HR. PCG measures mechanical vibrations caused by myocardial contraction, valve opening and closing, blood acceleration, and other factors in the cardiac cycle. Compared with ECG, PCG can measure more heart rate information, such as the third heart sound (S3), which reflects rapid left ventricular distension along with increased atrioventricular flow.(Shorno, A., Mori, S., Yatomi, A., Kamio, T., Sakai, J., Soga, F., Tanaka, H., Hirata 2019), shown in Figure 1, but because the larger heart sound sequences are weak, filtering and amplification are required to obtain the signal, resulting in a more complex processing procedure. ACG is a recording of chest wall movement above the apex of the heart.(Tippit, H., Benchimol 1967). Apex pulsation will cause chest wall movement. Therefore, a pressure sensor attached to the chest can measure the peak rate to obtain the HR signal.

Optical fibers that have a singlemode-tapered multimode-singlemode structure (tapered SMS fiber) are designed by connecting two singlemode fibers with multimode fibers. SMS type optical fibers are composed of a pair of identical singlemode fibers connected at the ends of the multimode fiber (Kusumah 2019). In the multimode fiber section, a tapered fiber configuration is made. Tapered fiber can be made using several methods, such as flame heating techniques and wet engraving techniques. Figures 2 (a) and (b) show the SMS fiber diagrams before and after the tapered fiber formation process. We know that the initial diameter of the multimode fiber is 125 μm, but after the tapered fiber formation process, the fiber diameter is reduced. This difference in size causes the mode that travels through the taper fiber to leak. Light traveling along the singlemode fiber through the taper area in the multimode fiber will produce evanescent waves (Zhao, Y., Cai, L., and Hu 2015). This makes the fiber sensitive to external factors. For example, a refractive index sensor will respond to changes in the refractive index due to evanescent waves. The light will experience mode leakage and be absorbed by the surrounding environment.



(a) (b)

Figure 2 :SMS structured optical fiber schematic (a) before and, (b) after tapered fiber formation

The connection between optical fibers must be connected evenly along the axis to prevent the emergence of higher order mode excitation at the lead-in connection area between singlemode and multimode and at the lead-out connection of multimode fiber. Given that the core diameter of step index multimode fiber is much larger than that of singlemode, only lower order fundamental modes can be produced LP01 and directed inside the fiber (Hatta 2009).

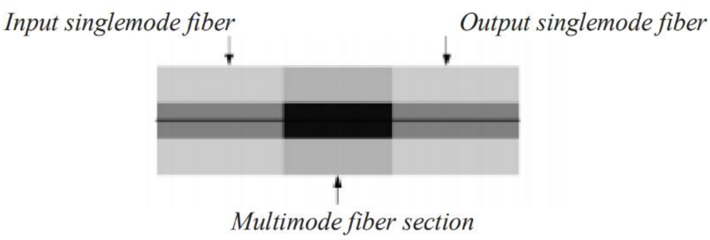


Figure 3: Singlemode-multimode step-indexsinglemode (SMS) optical fiber

The waveguide phenomenon in optical fiber with SMS structure can be explained through mode propagation analysis (MPA). In general, the power loss of SMS optical fiber can be expressed by the following formula (Yang Li 2014).

$$(1) P_{out}(L) = 10log\left[\left|\sum_{n=1}^{N} \eta_{n^2} \exp\left(j\beta_n L\right)\right|\right]^2$$

Where L refers to the multimode length, ηn and βn are the excitation coefficient and propagation constant of the LP0n mode, and N represents the number of modes entangled in a multimode optical fiber with a step index. To understand the number of modes entangled in a multimode optical fiber with a step index, we can approach it by calculating the normalized frequency (Yang Li 2014).

$$V = k_0 a_M \sqrt{n_{inti}^2 - n_{kulit}^2} \quad (2)$$

In this case, aM, $k0$, $ninti$, and $nkulit$ refer to the step index multimode radius, the wave number in vacuum, the core refractive index, and the skin refractive index, where the skin refractive index is the refractive index of the breathing air. Furthermore, to determine the dispersion constant of each mode, the following formula can be used (Yang Li 2014).

$$\beta_n = k_0 n_{eff}^{(n)} \quad (3)$$

Where $neff$ is the effective refractive index of the LP0n mode. Meanwhile, the excitation coefficient of each mode can be calculated by performing an overlap integral between the input field distribution and the field distribution of each guided mode.

In a study conducted by Yong Zhao and colleagues on the use of taper-shaped SMS fibers as refractive index sensors, a sensor sensitivity of 261.9 nm/RIU was found in the range of 1.3333–1.3737. In the taper area, the strongest modes tend to leak more easily into the liquid with a refractive index, which is usually referred to as evanescent waves (Zhao, Y., Cai, L., and Hu 2015).

Ricardo M. André and his team conducted a study utilizing the multimode interference (MMI) phenomenon that occurs in tapered fibers as sensors for measuring strain and temperature. In this study, the fiber structure used was singlemode-multimode coreless-singlemode (SMS) fiber. When strain occurs, the self-imaging produced by the MMI in the taper area will experience a pattern shift, so that the output power becomes greater. This causes the strain sensitivity to increase. The length of the multimode fiber connected to two singlemode fibers is 50 mm. The strain sensor shows a sensitivity of −23. 69 pm/με for a taper diameter of 15 μm. The resolution for the strain and temperature sensors is ±5. 6 με and ±1. 6°C, respectively (André, RM, Biazoli, CR, Silva, SO, Marques, MB, Cordeiro, CMB and Frazão 2013).

The refractive index sensor based on singlemode-multimode-singlemode (SMS) fiber uses Thorlabs AFS105/125Y stepindex MMF multimode fiber with a length of 42 mm. In the SMS fiber structure, the multimode fiber is formed into a tapered fiber. The resulting sensitivity is 1913 nm / RIU and about 5.23 × 10-6 RIU at a refractive index of about 1.44 (Wang, P., Brambilla, G., Ding, M., Semenova, Y., Wu, Q., and Farrell 2011). Research on refractive index sensors based on multimode interference (MMI) on tapered SMS fiber was conducted by Claudecir R. Biazoli and team. The multimode fiber used is multimode coreless. The length of the multimode fiber is 20 mm with an initial diameter of 125 μm which shrinks to 55 μm after the taper process with the flame brushing technique. The refractive index range of 1.30 – 1.33 has a sensitivity of 148 nm/RIU, while in the range of 1.42 – 1.43, the sensitivity reaches 2946 nm/RIU (Biazoli, CR, Silva, S., Franco, MAR, Frazão, O., and Cordeiro 2012).

Sensors are generally defined as devices that receive stimuli and provide responses in the form of electrical signals. These stimuli are certain conditions in the environment that can be detected or taken by the sensor (Fraden 2016). In a measurement system, the sensor acts as the first element that produces an output signal based on the function of the input of a number of certain physical quantities (Bentley 2005). Sensor characteristics are the performance of a sensor. Sensor characterization is carried out to evaluate the performance of the sensor that has been designed. One of the characteristics of a sensor is static characteristics, which include span, range, linearity, sensitivity, resolution, and hysteresis (Fraden 2016).

Span refers to the measurement range in which the sensor is still able to respond to the received stimulus. The sensor measurement range can be found at the sensor input or output. The input range is calculated from the difference between the maximum and minimum input values, while the output range is also calculated from the difference between the maximum and minimum output values. The input range includes values from the minimum to the maximum input. While the output range includes the minimum to the maximum output values. Linearity is an ideal characteristic in a measurement system. Sensitivity describes the extent of the sensitivity of a sensor. Sensor sensitivity can be assessed from the comparison of changes in output compared to changes in input. Resolution is a condition when the largest change in input does not cause a change in sensor output. Hysteresis shows the difference in sensor output values obtained from measurements that increase and decrease at the same input value.

4 Conclusion

Tapered fiber optics have great potential as a non-invasive sensor technology for detecting cardiac arrhythmias. The working principle is based on the interaction of evanescent fields with the external environment, allowing for sensitive and real-time detection of microscopic mechanical fluctuations, such as heart rate and blood pressure. Studies have shown that this sensor can be used as an alternative to electrocardiogram (ECG), especially in wearable applications and IoT-based remote monitoring.

Compared with conventional methods, tapered fiber-based systems are superior in terms of sensitivity, portability, and freedom from electromagnetic interference. However, technical challenges such as long-term stability and system integration compatibility are still the focus of further development.

The use of this technology can pave the way for a more adaptive and personalized health monitoring system, encourage the implementation of e-health and support early diagnosis of cardiovascular disorders. Future recommendations include further experimental research, system miniaturization, and multidisciplinary collaboration between physics, biomedicine, and engineering to realize a precise and widely accessible arrhythmia detection system.

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