An Optical-ID Sensor Tag with an All-Fibre Antenna for Remote FBG Sensors

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***Abstract*— RFID sensors have been widely used in the Internet-of-Things. This paper presents a novel optical counterpart, a wireless optical-ID sensor tag leveraging a 45º tilted fibre grating as an optical antenna and an in-fibre diffractive device for wavelength demodulation of a FBG sensor.**

***Keywords*— Optical ID, optical sensors, optical antenna, tilted fibre grating, internet of things**

I. INTRODUCTION

Radio frequency identification (RFID) sensors are widely utilized in the Internet-of-Things (IoT) due to their low cost and extensive range of applications, from inventory management to asset tracking [1]. However, RFID sensors have notable limitations, particularly their susceptibility to harsh environments characterized by strong electromagnetic interference, which can significantly impair their functionality and reliability. In contrast, optical fibre sensors, in particular fibre Bragg grating (FBG) sensors, present a compelling alternative, offering several inherent advantages such as compactness, and low weight [2]. Moreover, their electrical insulating properties make them ideal for environments where electromagnetic interference is a concern.

Conventional FBG sensors are typically passive devices that must be connected to a demodulation system via optical fibre cables. This requirement poses significant limitations on the implementation of wireless optical fibre sensors, akin to RFID sensors, due to the lack of integrated optical antennas for effectively receiving and transmitting optical carrier signals.

This paper presents the optical counterpart to RFID sensors: a novel wireless optical ID sensor tag design. To overcome the aforementioned limitations, a 45º tilted fibre grating (TFG) is employed as a highly-efficient optical antenna, fully compatible with optical fibre sensors. In addition, this design enables a promising solution for low-cost wavelength demodulation of optical fibre sensors, by utilizing the same TFG as an in-fibre diffraction gratin for simultaneous wavelength separation. This innovative two-in-one design of the 45º TFG enables an all-fibre solution for wireless optical-ID sensor tags and significantly simplifies wavelength demonstration for optical sensors.

II. PRINCIPLE

Figure 1 illustrates the comparison between the well-developed RFID sensor system and the proposed wireless optical ID sensor system. RFID sensor tags typically consist of an electronic sensor, a chip with memory, and an antenna, which work together to wirelessly transmit data to a RF reader. In the presented wireless optical ID sensor system, the optical sensor tag comprises FBG sensors and a 45º TFG imprinted in the same piece of optical fibre.

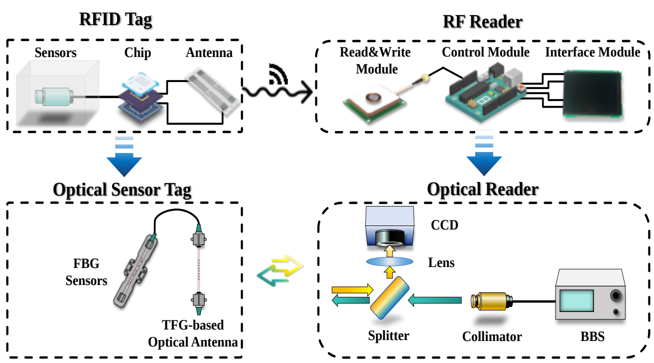

Fig. 1. Comparision between the conventional RFID sensor system (top) and the proposed wireless optical ID sensor system. CCD: charge-coupled device camera; BBS: broadband optical source.

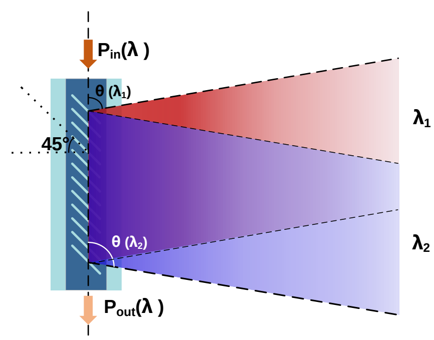

Fig. 2. Schematic of a 45º TFG showing its lateral light coupling and wavelength decomposition capabilities.

The in-fibre grating structure with an inclination angle of 45º laterally couples light out of the fibre core, eliminating the need for a refractive index matching liquid to overcome the obstruction of the optical fibre cladding. This characteristics improves its performance in duplex light coupling between optical fibre core and free space [3]. Additionally, the radiation mode of the 45º TFG offers light-splitting capacity [4]. It can emit light at various angles and decompose complicated broadband light into monochromatic light at different angles, as illustrated in Fig. 2. This makes it an excellent candidate for a highly-efficient optical diffraction grating, with over 99% diffraction efficiency. It is a crucial component for optical wavelength demodulation when used with a charge-coupled device (CCD) sensor array.

III. Results

Experiments are carried out to verify the proposed approach. We design a wireless optical ID sensor system based on Fig. 1. The optical sensor tag consists of a FBG sensor and a single 45º TFG attached to the sensor for simultaneous wireless light coupling and wavelength analysis. The optical reader system, also shown in Fig. 1, in integral to the setup.

An optical signal from a broadband optical source (BBS) with a central wavelength of 1550nm is collimated by a fibre collimator and then emitted into free space. The transmitted light, passing through an optical beam splitter, is directed to the wireless optical sensor tag. The 45º TFG, functioning as the optical antenna, receives the optical signal and routes it to the connected FBG sensor. The reflected signal from the FBG sensor is diffracted back into free space via the same 45º TFG antenna and collected by the optical reader. Different wavelength components of the light beam are diffracted with different angles due to the angular dispersion property of the integrated TFG. A cylindrical lens and convex lenses in the optical reader focus the diffracted beam on to a NIR CCD camera (CinCam CMOS-1202-IR) routed by the beam splitter. The wavelength of the optical signal from the FBG sensor can be determined from the position of the focused spot on the camera.

We characterize the performance of the 45º TFG as a duplex optical antenna for wireless optical signal coupling, and as an optical diffractive device for wavelength analysis. When acting as a transmitting optical antenna, the TFG offers an average diffraction efficiency of 93.5% over a 30 nm wavelength bandwidth [5], by carefully aligning the polarization state of the light in the fibre core. As a receiving optical antenna, the 45º TFG incurs a coupling loss of ~11 dB from free space to optical fibre [6]. This high loss is attributed to the lack of anti-reflection coating on the fibre and the limited reception wavelength window.

To evaluate the utility of the 45º TFG in wavelength analysis, we replace the FBG sensor in the optical tag with a broadband optical fibre Faraday rotating mirror. This setup allows us to precisely characterize the system's performance by emitting single-wavelength light using a tunable laser in the optical reader. We considered four specific wavelengths: 1550, 1553, 1556, and 1559 nm. Figure 3 shows the measured results captured by the CCD camera (left column). The positions of the focused spots on the camera correspond to the optical wavelengths, as demonstrated in the right column. By extending our measurements to include additional wavelengths, we confirmed an excellent linear relationship between the wavelength and the spot position. This relationship was quantified with a linear fitted R^2 value exceeding 0.999, indicating high precision and reliability in wavelength demodulation using the 45° TFG. This result validates the effectiveness of the 45° TFG in providing accurate wavelength analysis within the wireless optical ID sensor system.

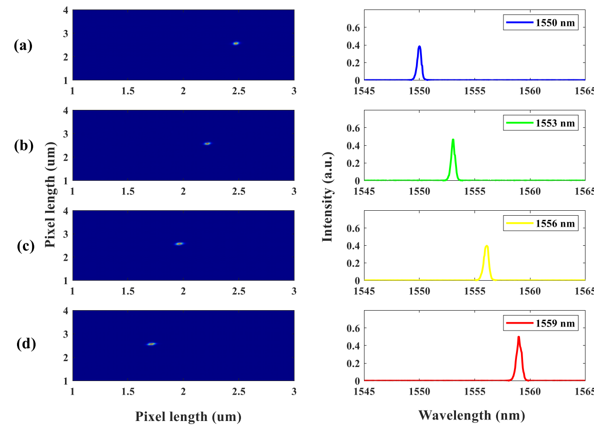

Fig. 3. Experiment results for wavelength demodulation. Left: signal detected by the CCD camera with their positions indicating the wavelength. Right: demoduated wavelength informatin according to the linear callibration process.

IV. Conclusion

In conclusion, we have demonstrated a novel wireless optical ID sensor system utilizing a 45° tilted fibre grating (TFG) integrated in the sensor tag as an efficient optical antenna for both signal coupling and wavelength analysis. Our experimental results show that the TFG provides high diffraction efficiency and accurate wavelength demodulation. This innovative approach addresses the limitations of conventional wired optical fibre sensors, offering a promising alternative for harsh environments where traditional RFID sensors may fail. Future work will explore further optimization and real-world applications of this technology.

References

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