High-Sensitivity and High-Precision RI Sensing Using THz-Comb-Based Frequency Multiplication and Dual-Comb Active-Dummy Temperature Compensation

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Abstract. This paper presents a novel optical-comb-based refractive index sensor that simultaneously achieves high-sensitivity and high-precision by combining THz-comb-based frequency multiplication with active-dummy temperature compensation in a dual-comb configuration. In this approach, a little RI-induced shift of the comb mode spacing (f_{rep}) is frequency-multiplied via THz frequency comb, while the dual-comb scheme compensates for temperature drift in f_{rep}. Experimental results demonstrate a 3100-fold improvement in RI sensitivity and a 10-fold enhancement in measurement precision.

1 Introduction

Optical frequency combs (OFCs) have recently emerged as novel photonic radio frequency (RF) fiber sensors for precisely measuring the refractive index (RI) of liquids [1]. In a fiber-based OFC integrated with an intra-cavity multi-mode interference (MMI) sensor, variations in sample RI are converted into changes in the comb mode spacing (f_{rep}). However, the RI-dependent shift in f_{rep} is typically very small, on the order of tens to hundreds of hertz which necessitates its amplification to achieve high sensitivity. Moreover, temperature drift of sensor signal (f_{rep}) significantly affects measurement precision.

In this study, we overcome these challenges by combining THz-comb-based frequency multiplication to enhance sensitivity [2] with active-dummy temperature compensation using a dual-comb configuration to reduce the temperature drift [1].

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2 Principle of operation and Result

When the optical comb is incident on a photoconductive antenna (PCA), a PC - THz comb is generated by extending the higher-order harmonics of f_{rep} into the THz region, as shown in Fig. 1(a). Heterodyne mixing with a known CW - THz wave (freq. = f_{THz}) generates a beat signal (f_b) of the m-th harmonic (freq. = mf_{rep}) closest to f_{THz}, thereby enhancing the RI sensitivity by a factor of m. In this study, m was set to 3300 during the measurements. Furthermore, beat signals $f_{b(Active)}$ and $f_{b(Dummy)}$ are generated by using an active comb sensitive to both RI and temperature and a dummy comb sensitive to only temperature, corresponding to each source. With the addition of a common CW - THz wave, $\Delta f_b = f_{b(Active)} - f_{b(Dummy)}$ can be measured, enabling high-sensitivity and high-precision measurements, as shown in Fig. 1(b).

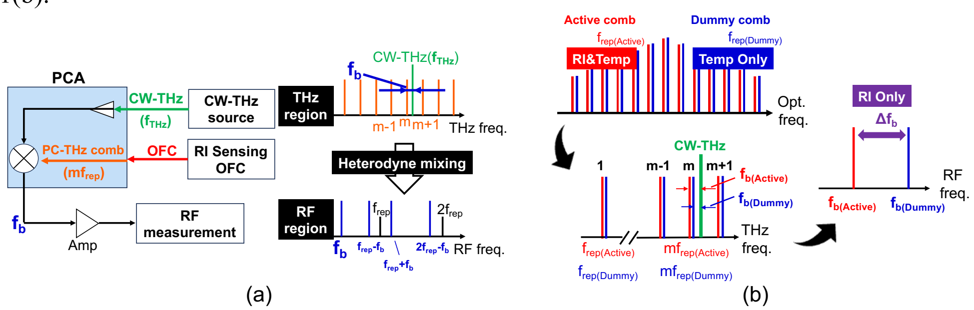

Fig.1. (a) Generation of the THz comb and the f_b signal by a PCA.
(b) Temperature compensation and high sensitivity achieved by the Δf_b signal.

Ethanol-water solutions with different concentrations (RIs) were used as experimental samples. As shown in Fig. 2(a), the RI sensitivity in the f_{rep} measurement was 9.196×10^3 Hz/RIU. However, as shown in Fig. 2(b), measuring the f_b signal improved the sensitivity to 3.013×10^7 Hz/RIU, achieving a 3300-fold enhancement in measurement sensitivity. In this case, the RI precision, calculated using the root mean square error (RMSE), was 1.330×10^{-3} RIU. Furthermore, as shown in Fig. 2(c), by measuring the Δf_b signal, a similar RI sensitivity was maintained, and the RI precision, also calculated using RMSE, was improved to 1.144×10^{-4} RIU, resulting in a 10-fold improvement in measurement accuracy.

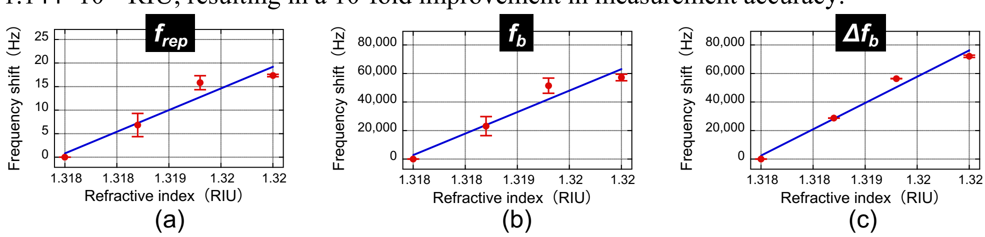

Fig.2. Results of RI measurement based on (a) f_{rep}, (b) f_b and (c) Δf_b measurements.

References

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