Plasmonic extra-ordinary transmission: testing the maintenance of optical frequency and phase via a frequency comb

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ABSTRACT

Frequency comb has shown remarkable potential in time/frequency metrology, atomic/molecular spectroscopy and precision LIDARs. It will create novel possibilities in nano-photonics and plasmonics; however, its interrelation with surface plasmons is unexplored despite the important role that plasmonics play in nonlinear spectroscopy and quantum optics through the manipulation of light in a subwavelength scale. We demonstrate that frequency comb can be transferred by plasmonic nanostructures without noticeable degradation of less than $6.51 \times 10^{-19}$ in absolute position and 1 Hz in linewidth, which implies frequency comb’s potential applications in nanoplasmonic spectroscopy, quantum metrology and subwavelength photonic circuits.

Keywords: Frequency comb, plasmonics, extra-ordinary transmission, plasmonic phase

1. INTRODUCTION

Coupling surface plasmons (SPs), collective charge oscillations produced by the resonant interaction of light and free electrons on the interface of metallic and dielectric materials [1,2], into frequency comb [3-5] creates numerous advantages. First, SP can allow for the frequency comb to access nanoscopic volumes that surpass the diffraction limit. Second, the field enhancement by localized SP enables the highly sensitive detection of weak signals, even from a single molecule. Third, next-generation photonic devices and circuits can be implemented within a small subwavelength volume by all-optical control of light properties in plasmonic nanostructures within ultrafast time scales. However, the superior performance of the frequency comb, such as absolute frequency uncertainty, high frequency stability and narrow linewidth, could deteriorate during the photon-plasmon conversion process. We report that frequency comb successfully maintains core performances, especially in terms of optical frequency and phase information, during the photon-plasmon conversion by exploiting plasmonic extraordinary transmission through a subwavelength plasmonic hole array. This implies that the original frequency comb can be transformed into a form of plasmonic comb on metallic nanostructures and reverted to an original frequency comb without noticeable degradation in absolute frequency position, stability and linewidth [6]; this can be also applied to high-precision measurement of optical phase changes around the plasmonic samples.
2. PLASMONIC EXTRA-ORDINARY TRANSMISSION: SYSTEM DESIGN AND DEVELOPMENT

Figure 1 shows the experimental apparatus to characterize the conservation of frequency comb for the conversion from photon to surface plasmon. The frequency comb is split into reference and measurement beams; one part of the beam transmits through an acousto-optic modulator (AOM) for a frequency shift of 40 MHz to construct a reference frequency comb and the other part of the beam passes through the plasmonic sample. The frequency comb structure in SP resonance was generated by the exploitation of a metallic nanohole array used for extraordinary optical transmission (EOT) that converted photon into SP [7,8] (See Figure 2.). The small diameter of each hole prevents light passing through the sample based on classical optics. However, the SP-mediated tunneling effect of nanohole array drastically enhances optical transmittance. The physical origin of EOT has been attributed to resonant surface plasmon polaritons (SPP). The detection of the heterodyne beat frequency generated by the interference between the reference and measurement beams enables the measurement of optical frequency difference, at a radio-frequency (RF) regime using a fast avalanche photodiode. This resultant frequency difference can be simplified to \( f_{\text{AOM}} - \Delta f_{\text{sp}} \), where \( f_{\text{AOM}} \) works as the high frequency carrier to isolate \( \Delta f_{\text{sp}} \) from the relatively strong DC (zero frequency) noise components.

Figure 1. Frequency comb transferred by plasmonic extra-ordinary transmission.

Figure 2. Metallic nanostructure for plasmonic extra-ordinary light transmission.
Figure 3 shows the simulated and experimentally measured plasmonic field distribution through the optimized EOT sample. The electric field around the hole was significantly enhanced by surface plasmon propagation in the periodic apertures, delivering the optical energy through the hole. Minor deviations between the two spectrums are expected by focusing geometry onto the plasmonic sample. The polarization dependence of the EOT clarified that the transmission is made based on polarization-dependent plasmonic phenomena not simple optical transmission.

![Transmission spectrum through the plasmonic sample. Comparison of theoretical and experimental results](image)

3. PLASMONIC EXTRA-ORDINARY TRANSMISSION: OPTICAL FREQUENCY AND PHASE

The transmitted frequency combs through the plasmonic sample results in an interference with the reference frequency comb to verify the frequency comb structure after the photon-plasmon mode conversion by the EOT (See Fig. 4). For comparative analysis, interference signals were obtained at three different wavelength regimes with optical band-pass filters, representing on-resonance (840 nm) and off-resonance (800 and 900 nm) positions. The coherence of a large number of frequency comb modes can be deteriorated by temporal and spectral plasmonic dispersion, phase noise and frequency noise during the propagation through the plasmonic EOT sample. Therefore, the total summation of the electromagnetic waves at the output side of each hole may contain temporal and spectral dispersion, phase distortion and frequency change.
Linewidth broadening and S/N ratio reduction in plasmonic mode conversion process was initially evaluated by measuring RF beat linewidth of $f_{\text{AOM}} - f_{sp}$ at three different wavelength regimes (Fig. 5). With different resolution bandwidths (RBWs), there was no substantial degradation in the linewidth at 840 nm before and after the installation of the plasmonic sample in the beam path. The high-level S/N ratio of ~60 dB beat signal indicates that the plasmonic EOT provide no significant phase noise to the frequency comb.

Figure 4. Evaluation of the frequency comb transferred by plasmonic EOT. Conceptual diagram for generating the beat notes through the interference between two combs, one with and the other without plasmonic EOT.

Figure 5. The radio-frequency beat spectra measurement of plasmonically transmitted frequency comb and the reference comb.
Frequency stability was measured for the quantitative analysis of frequency-dependent noise contributions. The stability of the beat signal was measured to be $4.08 \times 10^{-18}$ without the plasmonic sample, $4.37 \times 10^{-18}$ with the plasmonic sample at resonance wavelength of 840 nm for an averaging time of 100 s, respectively (Fig. 6).

![Graph showing frequency stability](image)

**Figure 6.** Frequency stability of the frequency comb transferred by plasmonic EOT as an Allan deviation.

### 4. CONCLUSION

The frequency comb was transduced to plasmonic mode in the sample and reverted to photonic mode without significant changes in linewidth, frequency shift, signal-to-noise ratio, phase noise and Allan deviation. This outstanding frequency comb performance in plasmonic nanostructures enables a highly sensitive, high accurate and broadband measurement with direct traceability to standards. This inclusion of frequency comb has the potential to accelerate progresses in various plasmonic applications such as bio-chemical spectroscopy or sensing, quantum optics, and sub-diffraction-limit biomedical-imaging.

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### REFERENCES