Terahertz Fourier Transform Spectrometer Based on a Low-Reflectivity Fabry-Perot Interferometer

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Abstract: A simple THz Fourier transform spectrometer is demonstrated by using a low-reflectivity Fabry-Perot Interferometer. The emission spectra of a wavelength-tunable photonic transmitter excited by an optical coherent control system are determined by the spectrometer.

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OCIS codes: (300.6300) Spectroscopy, Fourier transforms; (120.2230) Fabry-Perot;

1. Introduction

With the aid of ultrashort laser pulses, terahertz (THz) technology has been developed with great progress. In past decades, many methods were proposed for generating and detecting the THz radiation and therefore many applications become realizable such as molecular recognition and material characterization. For promoting these applications, having a simple and reliable method for measuring the spectral characteristic of THz waves is as important as developing a high-power and high-efficiency THz emitter with tunable wavelength. For the spectral determination of the THz radiation, Fourier transform spectroscopy based on a Michelson Interferometer and THz time-domain spectroscopy (THz-TDS) based on photoconductive (PC) and electro-optic (EO) sampling are the most commonly used methods. However, the construction of the previous spectral characterization setup is complicated because of the invisibility of the THz waves and the long alignment distance. In addition, the setup of THz-TDS also has the disadvantage of immovability, not to mention that THz-TDS requires another intensive femtosecond optical pulse. Hence, a transmitted Fabry-Perot interferometer (FPI) which can be easily aligned with a visible light is proposed to perform the spectral analysis [1]. Taking the advantages of its compact size and movability, the Fabry Perot based spectrometer may be very attractive for many applications. But the complexity of spectrum reconstruction rises due to the interferences of multiple beams. In this paper, we propose a simple Fourier transform spectrometer based on a Fabry-Perot interferometer which has the merit of above methods. For eliminating the effect of multiple beam interference, a low-reflectivity Fabry-Perot spectrometer is adopted. In the case of low reflectivity, it will be shown that the interference is similar to the two-beam interference. So the spectrum can be reconstructed by taking a Fourier transform, which is just the same as the one-sided Fourier transform spectrometer. By utilizing this simple spectrometer, the emission spectra of a high-power and high-efficiency THz photonic transmitter [2,3] excited by an optical coherent control system are determined [4]. We will show that the central wavelength of the THz radiation from the photonic transmitter is tunable by changing the delay of coherent control system. Combining this tunable radiation source with the simple spectrometer, a powerful THz spectral sensing system suitable for many applications is thus demonstrated.

2. Theory and simulation results

Consider an ideal FPI consists of two parallel reflecting surfaces. If the two surfaces are identical and each has an intensity reflection coefficient R , the power transmission through the device for different spacing is given by

$$P_{out}(d) = \int P_{in}(f) T(d, f) df, \quad (1)$$

where

$$T(d, f) = \frac{1}{1 + H \sin^2\left(\frac{2\pi f n d \cos\theta}{c}\right)}, \quad (2)$$

$$H = \frac{4R}{(1-R)^2}, \quad (3)$$

and P_{in} is the power spectrum of the incident wave, n is the refractive index of medium between two surfaces, d is the spacing of the two surfaces, c is the speed of light in vacuum, θ is the angle from normal incident, and f is the frequency of radiation. Since the incident wave can be taken as a combination of various frequency components

with different amplitudes, we may first consider a wave with single frequency f_0 for simplicity. For eliminating the effect of multiple-beam interference, we choose a pair of low reflective surfaces. When the intensity reflectivity R is very low so that $H \ll 1$, equation (1) can be rewritten as follows.

$$P_{out}(d) = \frac{1}{1 + H \sin^2\left(\frac{2\pi f_0 n d \cos \theta}{c}\right)} \approx 1 - H \sin^2\left(\frac{2\pi f_0 n d \cos \theta}{c}\right) = \left(1 - \frac{H}{2}\right) + \frac{H}{2} \cos\left(\frac{4\pi f_0 n d \cos \theta}{c}\right) \quad (4)$$

From (4) we can observe that the transmitted power will approximate to a one-sided cosine function with the amplitude of $(H/2)$ and a dc value of $(1-H/2)$. Both amplitudes are affected by H only. By removing the dc value, we can retrieve a cosine waveform in the distance domain similar to the original waveform in the time domain. Comparing the distance domain signal with the time domain signal, the frequency of the former is $2ncos\theta/c$ times of the latter. Furthermore, since the cosine function is an even function which should be symmetrical about y-axis, we may mirror the one-sided signal about y-axis by letting $P_{out}(-d) = P_{out}(d)$. In this way, the spectrum can be reconstructed by taking a Fourier transform of P_{out} and scaling the frequency axis by multiplying a value of $c/2ncos\theta$. So there is a perfect mapping between original frequency and reconstructed frequency. The algorithm we adopt here is the same as the ordinary Fourier transform spectroscopy. The resolution of this spectroscopy is limited by the maximum spacing FPI can separate.

Fig. 1(a) Normalized power transmission of a Gaussian THz pulse with central frequency of 500 GHz and FWHM of 100GHz for various spacing d after removing the dc value (solid line) when $R=10\%$. The mirrored curve is shown in dashed line. (b) Reconstructed spectrum from the full trace plotted in Fig. 1(a) by taking the Fourier transform and scaling the frequency axis by multiplying $ccos\theta/2n$.

Fig. 1(a) shows the simulated power transmission for various spacing d after removing the dc value when $R=10\%$. The incident wave is assumed to be a Gaussian pulse with a FWHM of 100GHz and a central frequency of 500 GHz. The spectrum reconstructed by our algorithm is shown in Fig. 1(b). It can be observed that the reconstructed power spectrum restores the Gaussian peak located at 500GHz with a FWHM of 100GHz, which is the same as the simulated incident wave. Unfortunately, the curve rises up slightly near 1THz. This harmonic comes from the interference between the wave transmitted directly and the wave transmitted after two bounces. As the reflection coefficient R increases, the harmonics become larger. Since the magnitude ratio of the second bounce to the first bounce wave is R^2 , the effect of harmonic is reduced by using surfaces of low reflectivity. Therefore, it is important to keep R sufficiently small to avoid the influence of the harmonics for broadband THz analysis. On the other hand, with a know reflectivity value, it is possible to remove the undesired harmonic effect through a simple numerical algorithm.

3. Experimental results

Recently, we have demonstrated a edge-coupled membrane photonic transmitter based on a high bandwidth-efficiency product MSM traveling-wave photodetector and a co-planar-waveguide fed slot antenna [2,3]. Because of its high power conversion efficiency, the photonic transmitter is suitable for many applications. For utilizing it as a narrow band THz emitter, an optical coherent control system is used to tune the central frequency of emission. This system has been previously demonstrated to have the capability to control the radiation frequency [4]. In order to further characterize the radiation spectra, the simple Fourier transform spectrometer based on a low-reflectivity Fabry-Perot interferometer is constructed. Fig. 2 shows the experiment setup of our THz excitation and

measurement system. To generate the optical excitation pulses with a fixed beat frequency, an 100fs optical pulse with a central wavelength of 850nm from a Ti:sapphire laser was first stretched to a linear chirp pulse of 8.7 ps by a grating pair. Then, a Michelson interferometer was used to tune the beat frequency by controlling the relative delay of two arms. The radiated THz wave was collected by two parabolic mirrors and the Fourier transform spectrometer was located between them. The Fourier transform spectrometer was made of two sapphire backed metal meshes as the partial reflective mirrors. The reflectivity of each mirror at the THz wavelength is controlled to be $\sim 10\%$. As the spacing between two mirrors changed, transmitted power detected by the bolometer changed too. Fig. 3 shows the measured THz power for different mirror spacing and the reconstructed radiation when the optical beating frequency was tuned to 460GHz. The measured THz spectrum shows a peak radiation frequency $\sim 442\text{GHz}$ which is close to the excitation frequency of the photonic transmitter and the FWHM of the radiation is $\sim 50\text{GHz}$. The experimental result reveals that the radiation from the photonic transmitter is also quasi-CW, following our expectation. This combined system with the simple THz spectrometer and the optically coherent controlled photonic transmitter thus provide us a reliable THz characterization tool for future spectroscopic applications.

In conclusion, we have demonstrated a simple Fourier transform spectrometer based on a low reflectivity FPI for spectral measurement. The spectrometer successfully characterizes the emission spectrum of an optically coherent controlled photonic transmitter. More characterization data on the photonic transmitter will be presented in the conference. Its limitation and comparison to other techniques will be also discussed.

Fig. 2. Experiment setup of the THz excitation and measurement system.

Fig.3. (a) Measured power transmission after removing the dc value when the excitation frequency is 460 GHz. (b) The reconstructed THz spectrum from (a)

4. References

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