Analysis on characteristic and application of THz frequency comb and THz sub-comb

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Abstract: In this paper, we proposed a method for THz sub-comb generation based on spectral interference. The result of our calculation indicated that the THz pulse train, generated by surface-emitted optical rectification of femtosecond (fs) laser pulse in periodically poled lithium niobate (PPLN), has a comb-like spectrum. The characteristic of this THz sub-comb was analyzed both in frequency and time domain. Compared with the THz frequency comb emitted by a photoconductive antenna (PCA), THz sub-comb has a lower spectral resolution and wider free spectral range. Thus it could be an ideal source for wavelength division multiplexing (WDM) in THz wireless communication system.

Key words: terahertz wave, frequency comb, optical rectification

1. Introduction

Optical frequency comb is a precision ruler in frequency metrology [1] and an ideal source in an optical communication system with wavelength division multiplexing [2]. In terahertz region, the output of a photoconductive antenna, triggered by a periodical train of fs laser pulses (fs optical comb), has a spectrum with a regular comb of sharp lines [3, 4]. The temporal form is an infinite series of periodic THz pulse train. As a THz frequency comb, it can be used to measure the frequency of a continuous-wave THz with high precision.

Similar to the THz comb mentioned above, a finite series of periodic THz pulse train also has a comb-like spectrum, but with the tooth (spectral components) coarser. Thus it is called coarse THz comb or THz sub-comb. It has been reported that the transmitted spectrum of a THz pulse through a multilayer filter is a sub-comb structure [5]. This filter has a one-dimensional dielectric multilayer
structure composed of alternating materials with high and low index of refraction. The main characteristic of this THz spectrum is attributed to THz pulses bouncing back and forth via multilayer structures.

The result of our calculation indicated that the surface-emitted THz wave, by optical rectification of femtosecond laser pulse in a periodically poled lithium niobate, can also be used as a THz sub-comb. The temporal form of radiated THz wave is a train of THz pulses with one single cycle. The polarities of every two adjacent pulses are opposite, and the number of pulses is proportional to the number of poled periods of the crystal. The physical mechanism of THz sub-comb generation was explained by spectral interference between early and late pulses.

The characteristic of THz sub-comb was compared with the THz frequency comb emitted by a photoconductive antenna. As a finite series of THz pulses, the spectral resolution of this sub-comb is not high enough for precision measurement. But with a wide free spectrum range, it is suitable for the source of THz wireless communication with wavelength division multiplexing.

2. Characteristic of THz sub-comb in frequency and time domain

The principle of narrow-band THz wave generation by surface-emitted optical rectification of fs-pulse in PPLN has already been discussed in detail by Avetisyan et al. [6, 7]. A sketch of surface-emitted geometry is shown in figure 1. In previous works [6, 7], the output THz wave is narrowband with one center frequency. The corresponding temporal form is quasi-harmonic.

If we change the structure of the PPLN and use larger poling period (e.g. 520µm), there would be multiple frequency components in the spectrum (figure 2). It is a comb-like spectrum, with the interval between every two adjacent components the same. The interval is inversely proportional to the poling period.

![Figure 1](image1.png)

**Figure 1** Surface-emitted geometry

![Figure 2](image2.png)

**Figure 2** Spectrum of THz sub-comb for the case poling period $\Lambda = 520$ µm
The corresponding waveform is presented in figure 3. Figure 4 is the expansion of the temporal region of -6~6 ps. Similar to the temporal form of mode-locked fs optical comb, which is a train of periodical fs laser pulses, the waveform of this THz radiation consists of a train of single cycle pulses. Here the number of pulses is 66, which equals to the number of interfaces between individual domains in the crystal (for the number of domains in PPLN is \( 2N+1 = 65 \)) and two surfaces of the crystal. As seen from figure 6, the polarities of every two adjacent pulses are opposite to each other.

![Figure 3 Calculated temporal form of THz sub-comb](image3)

![Figure 4 the expansion of the temporal region of -6~6 ps in Figure 3](image4)

As a train with 66 pulses, this THz radiation has a lower spectral resolution, compared with a frequency comb, which is an infinite series of pulses. Rigorously, it is not a THz frequency comb. But with a comb-like spectrum, we call it “THz sub-comb”. The spectral resolution (bandwidth of each component) in the comb-like spectrum is defined as: \( \Delta \omega = \frac{1.77c}{N\lambda} n \) [6]. For the case \( N = 32, \lambda = \lambda_2 = 260\mu m \) and the mismatch of refractive index \( n \) is 2.3, the bandwidth of one frequency component is 27.75GHz (circular frequency). The free spectral range (interval between two adjacent components) is \( 2 c/\lambda \), \( n = 3.14\text{THz} \) (the corresponding frequency, divided by \( 2\pi \), is 0.5THz).

3. mechanism of THz sub-comb generation

The mechanism of this surface-emitted THz sub-comb generation can be explained by spectral interference. According to figure 3, THz wave generated from a PPLN is a series of THz pulses. When a pump laser pulse travels through an interface between two adjacent domains of PPLN, one THz pulse is radiated, which has a wideband spectrum. Pulses, radiated from different domains,
“interfere” with each other. This behavior is spectral interference between early and late pulses [8].

The interference effect has accumulated by increasing the number of poling periods in LN crystal. As
a periodical continuation of one THz pulse, the THz pulse train emitted from a PPLN has a
quasi-discrete spectrum, which is on the analogy of mode-locked fs optical frequency comb [1].

Only at the condition of constructive interference, the certain frequency components can arise in
the output spectrum (peak values in figure 2). The condition can be expressed as:

\[ \omega = (2k + 1) \frac{\pi c}{l \Delta n}, k \in \mathbb{N} \]  

(1)

Not only the fundamental frequency \((k = 0)\), but also high-order harmonics \((k = 1, 2 \ldots)\) satisfy
this condition. Thus, there could be multiple frequency components in the output spectrum
(comb-like spectrum).

4. comparison with THz frequency comb

For the THz frequency comb emitted by a PCA, when a mode-locked femtosecond laser pulse train is
incident on the antenna gap of a photoconductive film, a periodical THz pulse train is radiated. In the
frequency domain, the optical frequency comb is down-converted to the THz region without any
change in its frequency spacing. As an infinite series of periodic THz pulse train, it has a high
spectral resolution \(~11\text{MHz}\) (the corresponding free spectral range is \(81.8\text{MHz}\)) [3]. This THz
frequency comb is quite suitable for measurement of the frequency of a continuous-wave THz with
high precision.

As calculated above, the spectral resolution of THz sub-comb is \(\Delta \nu = 4.42\text{GHz} = (27.75\text{GHz}/2)\)
and the free spectral range is \(0.5\text{THz}\), which is much wider than . Compared with the THz
frequency comb , THz sub-comb has a lower spectral resolution and wider free spectral range. The
THz sub-comb will be an ideal source for wavelength division multiplexing in THz wireless
communication system, for it can be separated into its individual components easily for
demultiplexing and modulation of each channel.

5. conclusion

In this paper, we proposed a method for THz sub-comb generation based on spectral interference by
surface-emitted optical rectification of fs laser pulse in PPLN. The result of our calculation indicated
that the surface-emitted THz wave has a comb-like spectrum and the corresponding temporal form is
a train of THz pulses, if the structure of PPLN is designed properly. The physical mechanism of this
phenomenon was explained by spectral interference between early and late pulses.

The characteristic of THz sub-comb was compared with the THz frequency comb emitted by a
photoconductive antenna. As a finite series of THz pulses, this calculated THz radiation has a lower
spectral resolution. However, with a wide free spectrum range, this sub-comb can be easily separated
into its individual components for demultiplexing and modulation of each channel. So it could be an
ideal source for wavelength division multiplexing in THz wireless communication system.

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