Suppression of the Fluctuation Effect in Terahertz Imaging using Filtering

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Abstract—To suppress the fluctuation effect due to laser power instability and terahertz radiation fluctuation, different types of filtering method are proposed to process the terahertz images obtained from a pulsed terahertz raster scanning imaging system. The physical model of filtering for terahertz imaging is established. The mathematical expressions are given with the specific physical meaning in accordance with the imaging principle. To demonstrate the effectiveness of the method, a filtering experiment based on two raw terahertz images obtained from the femtosecond laser using a continuous-wave (CW) terahertz source is performed. The effect of the method and the advantages of different filtering are discussed. The pulsed- and CW-terahertz image processing results both show that in addition to suppressing the fluctuation effect, the method can also enhance target imaging.

Key words: Fluctuation Effect, Filtering

I. INTRODUCTION

Terahertz imaging has undergone rapid development since its initial stages¹. In terahertz imaging, the fluctuation of gray level distribution cannot be avoided because of the fluctuation effect from the terahertz source, whether the source is pulsed or continuous wave (CW). To overcome the fluctuation effect with time, three calibration methods are generally utilized. In the first method, a second reference background image is obtained simultaneously or within a transient time scale. Afterward, the reference image is subtracted from the raw terahertz image. The result is a calibrated image with a mitigated background fluctuation effect. One example of this method is the dynamic subtraction method used in previous studies. Generally, this method requires a large number of raw images and reference images to improve the signal-to-noise ratio (SNR) of the terahertz images. In the second method, a linear relationship between the decreased terahertz signal and the measurement time is first obtained to determine the reference background intensities at any given time. Afterward, the reference background image is subtracted from the raw terahertz image to obtain a calibrated image. In the third method, the imaging object is first separated from the background to obtain a reference image for the background. The gray level at each line of the reference image is averaged to achieve a gray level estimation for each line. The estimation is then subtracted from the original image to mitigate the fluctuation effect. However, these three methods increase the complexity of the imaging experimental setup. Furthermore, except for the dynamic subtraction method in which the signal and background frames are alternately captured within millisecond timescales, the other methods cannot ensure that the reference images and terahertz images have the same degrees of fluctuation.

Here, we present a modified filtering method to simultaneously mitigate the fluctuation effect and enhance object imaging. We first establish a physical model and then demonstrate the feasibility of the principle. Afterward, based on our experimental results, the real effect of this method is illustrated. To illustrate the principle of this method in CW terahertz imaging experiments, we select two raw CW terahertz images from the experiment for filtering. The results are then compared with those of the real images.

Finally, a brief discussion on the usage and limitation of this method is given. Homomorphic filtering is commonly used to suppress multiplicative noise, such as non-uniform illumination background, in visible images. This method has been adapted to suppress the non-uniform illumination effect in medical imaging and remote sensing. However, fluctuations occur in both pulsed and CW terahertz radiation sources when a raster-scan is performed to obtain the terahertz image. The fluctuation is then transferred to the gray level distribution of the terahertz image, which results in severely degraded imaging quality. According to the peak-to-peak amplitude terahertz imaging principle, if other kinds of additive noise are not taken into consideration, the two-dimensional (2D) gray level distribution for terahertz transmission images can be represented as the product of the terahertz radiation power \(i(m, n)\) that is incident on the surface of the imaging targets and the transmission coefficient \(t(m, n)\). Meanwhile, the 2D gray level distribution for terahertz reflection images can be represented as the product of the incident terahertz power \(i(m, n)\) and the reflection coefficient \(r(m, n)\). \(m\) and \(n\) are the coordinates of the 2D distribution in the spatial domain. The 2D distribution of the transmission coefficient or of the reflection coefficient contains information on the imaging targets. We hope to distill this information, but the fluctuation effect of the terahertz radiation power \(i(m, n)\), which acts as the multiplicative noise, blends with this information. The fluctuation effect and imaging information are coupled in the spatial domain. Therefore, these two parts are not separable in the frequency domain, and a mere high-pass filtering in the frequency domain will indiscriminately operate on the frequency components of both parts and will not achieve good results.

II. FILTERING

The trick of image filtering is that you have a 2D filter matrix, and the 2D image. Then, for every pixel of the image, take the sum of products. Each product is the color value of the current pixel or a neighbor of it, with the corresponding value of the filter matrix. The center of the filter matrix has to be multiplied with the current pixel, the other elements of the filter matrix with corresponding neighbor pixels.

This operation where you take the sum of products of elements from two 2D functions, where you let one of the two functions move over every element of the other function, is called Convolution or Correlation. The
difference between Convolution and Correlation is that for Convolution you have to mirror the filter matrix, but usually it's symmetrical anyway so there's no difference.

A low-pass filter leaves the low frequencies alone. We expect a low-pass filter to smooth the image. This is good for removing noise, but blurs the image. A high-pass filter leaves the high frequencies alone. We expect a high-pass filter to sharpen the edges. This is good for edge detection.

To filter an image in the frequency domain:
- Compute $F(u,v)$, the DFT of the image
- Multiply $F(u,v)$ by a filter function $H(u,v)$
- Compute the inverse DFT of the result

Fig. 1: Basic filtering

III. SMOOTHING IS LOW-PASS FILTERING

Image smoothing actually is performing a low-pass filtering to the image. Edges and other sharp intensity transitions, such as noise, in an image contribute significantly to the high frequency content of its Fourier transform. Three commonly used low-pass filtering techniques

- Ideal low-pass filters
- Butterworth low-pass filters
- Gaussian low-pass filters

Simply cut off all high frequency components that are within a specified distance $D_0$ from the origin of the transform. Its drawback is that the filtering result has obvious ringing artifacts. Ideal low-pass filter is rarely used in practice.

Filter order can change the shape of the Butterworth filter; for high order values, the Butterworth filter approaches the ideal filter; for low order values, it approaches the Gaussian filter.

The ideal low pass filter is given in the fig 2 where all the a

High pass frequency is removed and we can get a smooth image.

Fig 2: Ideal low pass filter

The transfer function of a Butterworth low-pass filter of order $n$ with cutoff frequency at distance $D_0$ from the origin is defined as:

$$H(u, v) = \frac{1}{1 + (D(u, v)/D_0)^{2n}}$$

Fig 4 filtered image of blade by using butterworth low pass filter

The transfer function of a Gaussian lowpass filter is defined as:

$$H(u, v) = e^{-5(u,v)^2/2\delta^2}$$

where $D(u,v)$ is the distance from the center of the frequency rectangle.

Fig 5 filtered image of blade by using gaussian low pass filter

Gaussian filters used to remove blemishes in a photograph for publishing.

IV. SHARPENING IS HIGH-PASS FILTERING

Edges and fine detail in images are associated with high frequency components. High pass filters – only pass the high frequencies, drop the low ones. High pass filters are precisely the reverse of low pass filters, so,

$$H_{hp} = 1 - H_{lp}(u,v)$$
The construction of the homomorphic filter \( H(u, v) \) has been discussed above. The mathematical description of homomorphic filtering for terahertz transmission imaging will be discussed as follows.

The terahertz transmission images can be expressed as Eq. (2), where \( f(m, n) \) is the 2D gray level distribution of the terahertz transmission imaging.

\[
f(m, n) = i(m, n) \cdot t(m, n).
\]

Suppose, however, that we define

\[
z(m, n) = \ln f(m, n) = \ln i(m, n) + \ln t(m, n).
\]

Then,

\[
\text{FFT}[z(m, n)] = \text{FFT}[\ln i(m, n)] + \text{FFT}[\ln t(m, n)]
\]

or

\[
Z(u, v) = I(u, v) + T(u, v),
\]

where \( Z(u, v) \), \( I(u, v) \), and \( T(u, v) \) are Fourier transforms of \( z(m, n), \ln i(m, n) \), and \( \ln t(m, n) \), respectively. Then, we process \( Z(u, v) \) using the homomorphic filter function \( H(u, v) \) to obtain \( S(u, v) \) as

\[
\]

In the spatial domain,

\[
s(m, n) = \text{IFFT}[S(u, v)] = \text{IFFT}[H(u, v)I(u, v)] + \text{IFFT}[H(u, v)T(u, v)].
\]

By letting

\[
i'(m, n) = \text{IFFT}[H(u, v)I(u, v)], \quad \text{and} \quad t'(m, n) = \text{IFFT}[H(u, v)T(u, v)],
\]

Equation (7) can be expressed as

\[
s(m, n) = i'(m, n) + t'(m, n).
\]

The exponential operation for \( s(m, n) \) yields the desired enhanced image, which is denoted by

\[
g(m, n) = e^{i'(m, n)} \cdot e^{t'(m, n)}.
\]

The 2D gray level distribution of the homomorphic filtered images can be also expressed as

\[
g(m, n) = i_0(m, n) \cdot t_0(m, n),
\]

where \( i_0(m, n) = e^{i'(m, n)} \), \( t_0(m, n) = e^{t'(m, n)} \), \( i_0(m, n) \) and \( t_0(m, n) \) represent the outputs of the terahertz radiation and transmission components, respectively.

The mathematical equations can be adapted to terahertz reflection imaging simply by replacing the transmission coefficient \( t(m, n) \) with the reflection coefficient \( r(m, n) \).

With a homomorphic filter, a significant amount of control can be gained over the incident terahertz radiation component as well as on the transmission or reflection component. This control demands specification of a filter function \( H(u, v) \) that affects the low- and high-frequency components of the logarithmic-Fourier domain in different ways.

If the parameters \( H_l \) and \( H_H \) are set such that \( H_l < 1 \) and \( H_H > 1 \), the homomorphic filter function tends to decrease the contribution made by the low frequencies while amplifying the contribution made by high frequencies. Thus, the fluctuation effect of terahertz power radiation is sup-pressed, whereas the transmission or reflection components representing the detailed information of imaging objects are enhanced. The net result is a simultaneous dynamic range compression and contrast enhancement.
VI. GUI DESIGN

GUI is designed to provide the control over the sequence generator without touching the program. In Matlab, GUI can be created either by programming or by using Guide. In this GUI the pop-up menu is available to switch between different filter methods. The sequence will be generated by pressing the push button named ‘select the filter’, according to the inputs like filter order and cut off distance. Fig. 7 shows the GUI created for butterworth high pass filter, using pop-up menu any sequence can be selected. Also selection of filter having cut off distance 40 and order 2.

VII. CONCLUSION AND DISCUSSION

As we had seen different types of filtering, we can conclude that by using both low pass filter and high pass filter we can smooth and sharpen the images. Depend on the different filter order and different cut off distance we can get some fruitful results. As terahertz frequency emission was not constant we cannot maintain clear images but we can remove noises at some level by using these filters. However by using homorphic filtering we get some good results. However, this method cannot significantly improve the resolution of terahertz images, which is one of the key problems that hinder the development of terahertz imaging technology. To improve the terahertz image resolution and suppress other types of noise, we still have to use other image-processing methods combined with the imaging principles. High-resolution reconstruction methods such as the Lucy-Richardson method, projection onto convex sets, maximum a posteriori estimation, maximum likelihood estimation, and others have been used to improve the resolution of imaging systems. At present, high-resolution reconstruction for terahertz images is an interesting area of investigation.

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