OPTOELECTRONICS LETTERS Vol.8 No.4, 1 July 2012

Attenuation of terahertz transmission through rain

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(Received 10 February 2012)

Based on the Marshall-Palmer, Weibull raindrop size distribution and Mie electromagnetic scattering model, the relationships of attenuation coefficient of terahertz (THz) atmospheric window waves with precipitation rate and temperature are studied. Furthermore, combined with the loss of electromagnetic wave transmission in free space, the attenuation of THz communication and the transmission of current mobile communication signals through rain are compared and analyzed. The results show that the attenuation coefficient of THz transmission is increased with increasing precipitation rate, the difference of attenuation coefficient at different THz window waves is small, and the maximum difference is about 3 dB. The rain attenuation of THz wave is first decreased and then increased with increasing temperature, but the temperature has little effect on it. The attenuation of THz wave through rain is much larger than that of mobile communication signal.

Document code: A **Article ID:** 1673-1905(2012)04-0310-4
DOI 10.1007/s11801-012-1162-8

At present, for simulating atmosphere transmission characteristics of terahertz (THz) wave, some models are adopted[1-4]. However, the models have some limitations. Especially, the uncertainties of the scattering particle and time-space bring some difficulty in practical calculation and simulation[5].

Mie scattering is caused when the particle size is nearly equal to the wavelength of the incident electromagnetic wave[6]. As the raindrop particle size and the THz wavelength are in the same scale, the study of the effects of rainfall on the THz wave transmission is crucial. The impact of rainfall on the electromagnetic wave propagation in the infrared, ultraviolet, visible light and microwave bands has been widely studied[7-11]. These studies suggest that rainfall can cause the attenuation of electromagnetic energy, and even can make wireless communication link interruption in serious case. In the THz range, S. Ishii et al[12] calculated the rain attenuation at 313 GHz by using four raindrop size distributions, and found the simulation results by using Weibull distribution can be consistent with the Babkin's experimental results in 1969, but they only studied the rain attenuation when the rainfall intensity is in the range of 0−12 mm/h. Liu Xichuan et al[13] simulated the effects of rainfall intensity and temperature on rain attenuation at 0.3 THz, and found that the rain attenuation of THz wave is increased with increasing temperature and precipitation rate. But the studies did not use the atmospheric window waves, and did not consider the free-space transmission loss.

This paper studies the effects of rainfall intensity and temperature on transmission attenuation at THz atmospheric window waves. The results can be used for the THz wave wireless communications and space communications.

According to Lambert's law[14], the initial value of wave energy is set to I_0, and after the electromagnetic wave transmits for a length of L in rainy days, the wave energy can change into I which can be expressed as

$$I = I_0 \exp[-(K_\mathrm{e} + K_\mathrm{z})L] \ , \tag{1}$$

where K_z is the free-space transmission loss in dB,

$$K_\mathrm{z} = 92.44 + 20\lg(L) + 20\lg(f) \ , \tag{2}$$

where L is the propagation distance in km, and f is frequency in GHz. K_e is the rain attenuation coefficient which is a function of the raindrop function $N(D)$ and the raindrop extinction cross section Q_e. Assuming the incident wavelength is smaller than the distance between the raindrops, the rain specific attenuation K_e in dB/km is calculated by integrating all of the drop sizes as:

$$K_\mathrm{e} = 4.343\times10^3 \int_{D_{\min}}^{D_{\max}} Q_\mathrm{e}(D,\lambda,m)N(D)\,\mathrm{d}D \quad (\mathrm{dB/km}) \quad , \tag{3}$$

where Q_e is a function of the drop diameter D, the wavelength of the radio wave λ and the complex refractive index of the raindrop m, which is the square root of the complex dielectric permittivity ε

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$$m(f,T)=n(f,T)+\mathrm{i}\,k(f,T)=\sqrt{\varepsilon(f,T)}\ , \tag{4}$$

where ε (f, T) is the complex dielectric function which is a function of frequency and temperature. For determining the dielectric function of water, Liebe proposed the LH model in 1991[15]. This model can effectively simulate the dielectric constant of water in the range of 1 Hz−1 THz.

The attenuation cross section Q_e is found by applying the classical scattering theory of Mie for a plane wave radiation to an absorbing sphere particle. The cross section Q_e is expanded as

$$Q_e(D,\lambda,m)=\frac{\lambda^2}{2\pi}\sum_{n=1}^{\infty}(2n+1)\,\mathrm{Re}(a_n+b_n)\ , \tag{5}$$

where a_n and b_n are the Mie scattering coefficients.

Many raindrop size distributions have been proposed, such as Marshall-Palmer (M-P)[16], Joss-Gori[17], Weibull[18] and gamma[19]. M-P has the general common features of raindrop spectrum, so it has been widely used[20,21]. The simulation of electromagnetic wave transmission in rainy days also usually adopts Weibull distribution. S. Ishii et al[12] found that the simulation results by using the Weibull distribution are consistent well with the experiment results.

In the Weibull distribution,

$$N(D)=N_0\,\frac{c}{b}\left(\frac{D}{b}\right)^{c-1}\exp\left[-\left(\frac{D}{b}\right)^{c}\right]\ , \tag{6}$$

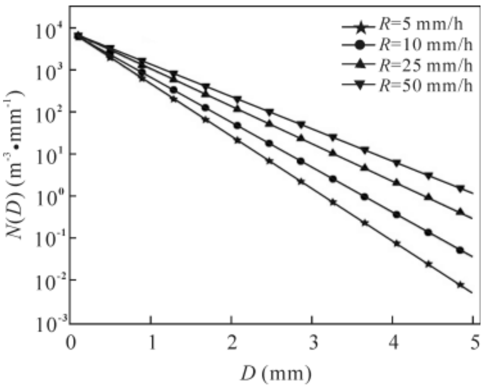
where N_0= 1000 m^{-3}, $b = 0.26R^{0.44}$ mm, $c = 0.95R^{0.14}$, and R is the precipitation rate in mm•h^{-1}.

In the M-P distribution,

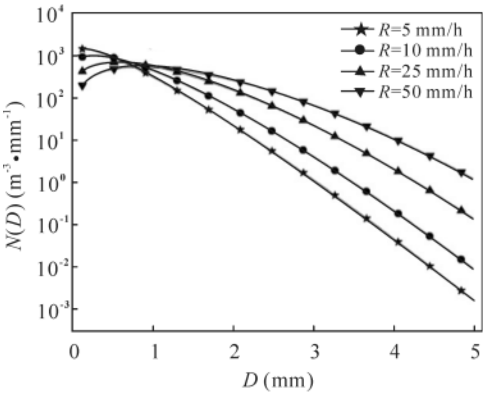
$$N(D) = N_0 \exp(-\zeta D)\ , \tag{7}$$

where N_0= 8×10^3 m^{-3}•mm^{-1} and $\zeta = 4.1R^{-0.21}$ mm^{-1}.

The changes of raindrop size distribution with raindrop diameter and precipitation rate simulated by using M-P and Weibull distributions are shown in Fig.1. Fig.2 shows the effects of precipitation rate and raindrop size distribution on the attenuation coefficients of different THz atmospheric window waves with wavelengths of 350 nm, 450 nm, 620 nm, 735 nm and 870 nm. From Fig.2, we can see that the attenuation coefficients of different atmospheric window waves are all increased with increasing rainfall intensity. This is because the greater the rainfall intensity, the more raindrops and bigger raindrops as shown in Fig.1, and the stronger the scattering of electromagnetic waves. The attenuation calculated by M-P distribution is larger than that by Weibull distribution, because the raindrops in M-P distribution are much more than those in Weibull distribution as shown in Fig.1. For the same rainfall, the longer the wavelength, the greater the rain attenuation, but the difference is small, and the maximum difference is only about 3 dB. It indicates that the difference of rain attenuation at different wavelengths can be ignored when the THz wave propagates through rain.



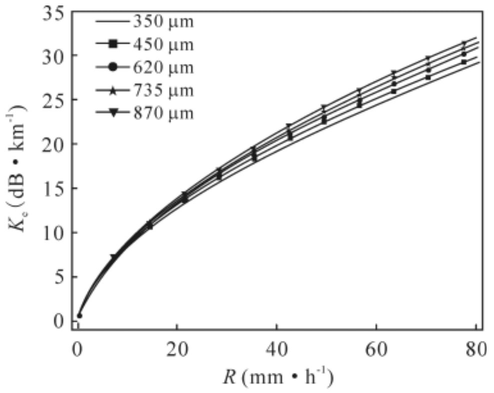
(a) M-P distribution



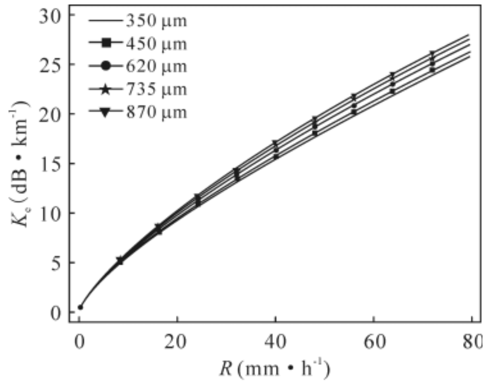
(b) Weibull distribution

Fig.1 Relationship between raindrop size distribution and raindrop diameter for different precipitation rates

According to the LH model, the complex refractive index of raindrop is related to temperature. We calculate the complex refractive indices of raindrops at different THz atmospheric window waves in the range of 274−310 K. As shown in Fig.3, the real part and imaginary part of the complex refractive index increase with increasing temperature and wavelength, and it changes the electromagnetic scattering



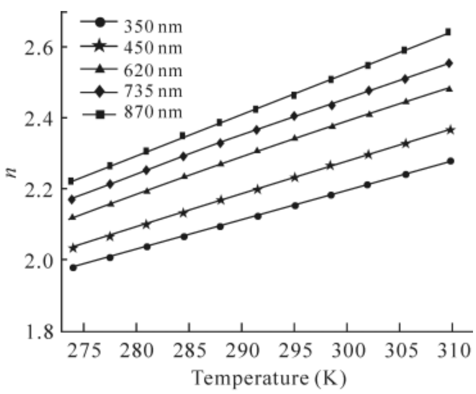
(a) M-P distribution



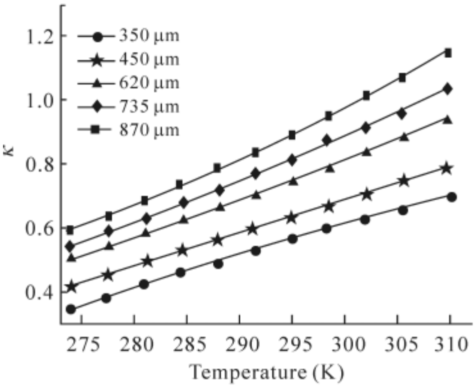
(b) Weibull distribution

Fig.2 Relationship between attenuation coefficient and precipitation rate for different wavelengths

intensity which is produced by raindrops. Fig.4 shows the effects of temperature on attenuation coefficient of THz waves by using Weibull raindrop size distribution when the precipitation rate is 10 mm/h. The vertical axis represents the variation of attenuation coefficient relative to the minimum attenuation coefficient at different temperatures and different THz atmospheric window wavelengths.



(a) Real part



(b) Imaginary part

Fig.3 Relationship between complex refractive index of raindrop and temperature

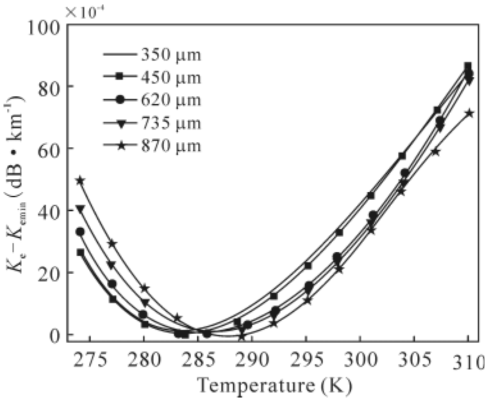


Fig.4 Relationship between the variation of attenuation coefficient of THz waves and temperature

Liu Xichuan et al[13] found that rain attenuation is slowly increased with increasing temperature at 300 GHz, but Fig.4 shows that the rain attenuation of THz wave is first decreased and then increased with increasing temperature, and the temperature of the minimum attenuation coefficient is increased with increasing wavelength. On the whole, the effect of temperature on the attenuation of THz wave transmission is weak, and the maximum variation is about 0.20%. It shows that the effects of temperature on rain attenuation of THz wave can be neglected, and the same transmission system can be applied under different temperature conditions.

From Eq.(1), we can know that when the electromagnetic wave transmits in the rain, the attenuation not only includes rainfall attenuation, but also includes the free-space transmission loss. According to Eq.(2), when the electromaagnetic wavelength is 350 μm and 870 μm, the free space loss is 151.1 dB/km and 143.2 dB/km, respectively. Thus, the loss caused by the rainfall attenuation is much smaller than the free-space transmission loss. Even when the rainfall intensity is 80 mm/h, the attenuation coefficient is also around 30 dB/km, as shown in Fig.2.

Generally, the frequency used for mobile communication is about 2000 MHz, and the free-space transmission loss is 106.3 dB/km, which is smaller than the THz wave free-space loss. We can see from Ref.[13] that the attenuation caused by the rainfall is increased with increasing frequency when the frequency is less than 300 GHz, and then the attenuation tends to be stable. It shows that the attenuation of THz wave transmission through rain is much larger than that of mobile communication signal. For meeting the requirements of the existing mobile communication system, the transmitter antenna gain and receiver antenna gain are increased, and relay communications[22] and a new code method[23] are adopted.

Rain attenuation at THz atmospheric window waves is calculated by using M-P and Weibull raindrop size distributions and Mie scattering electromagnetic wave transmission attenuation model. The rain attenuation of THz wave is increased with increasing rainfall intensity, and temperature has little effect on the rain attenuation of THz wave. The attenuation of THz wave transmission through rain is much larger than that of mobile communication signal. This paper just selects two representative raindrop size distributions, and bacause the rain type and raindrop size distribution have various characteristics, more extensive experimental and theoretical researches are needed.

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