Chapter 3 High-accuracy white light interferometry

3.1 Research background and objective

In the conventional white light interferometry (VSI), the height is obtained from the envelope peak position of the interferogram, and the accuracy is inferior to the phase shift method (PSI). Therefore, it has been proposed to improve the accuracy by using the phase information. Dändliker et al. (1992) performed two measurements, the VSI method and the PSI method, and used the height obtained by the VSI to determine the order of the PSI. Sandoz (1996) proposed the "white PSI method" that uses only the interferogram obtained by the VSI. This method is considered to be highly practical as a method for improving the accuracy of the VSI.

However, there are many problems, such as the error of height detection that affects the order determination and the so-called “wavelength jump” error and how to obtain the phase from the interference waveform that is not a single wavelength [Sandoz et al. 1997, Harasaki et al. 2000, Schmit et al. 2002, de Groot et al. 2002]. So, this technique has not been put to practical use as commercial machines. The author wanted to implement an algorithm based on the idea of the white PSI method on a commercial machine and clarify its performance and problems [Kitagawa 2007b].

3.2 Algorithm

We propose an algorithm that uses phase information in addition to amplitude information when calculating the height from the interference waveform obtained by the white light interferometry (named the WSI method, because it uses two pieces of information and the White-light phase-Shifting Interferometry). In this algorithm, the frame number N_p of the envelope peak and the relative phase φ_r at that position are calculated, and the height z is calculated by the following equation (Fig. 3-1).

$$z = N_p \Delta - (\lambda / 4\pi)\varphi_r \qquad (3\text{-}1)$$

where, Δ is the sampling interval, and λ is the equivalent illumination wavelength. The first term on the right-hand side is a component which corresponds the fringe order determined by the height estimation of the VSI method, and the second term is the correction term by the phase. Unlike the conventional VSI method, the estimation of the envelope peak position N_p requires little accuracy because it only determines the interference order.

For the phase calculation, the formula of the conventional PSI can be used if the sampling interval is set to about 1/4 cycle (corresponding to 90°) of the interferogram.

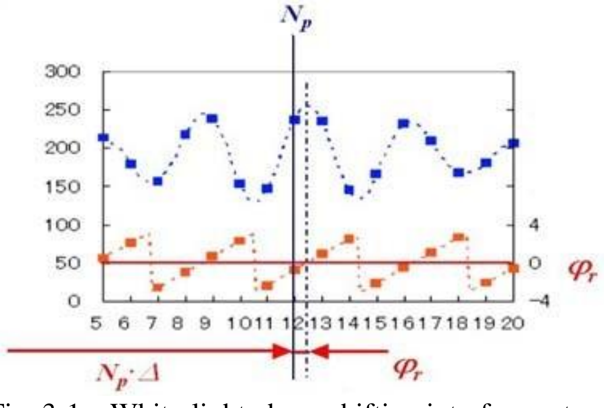


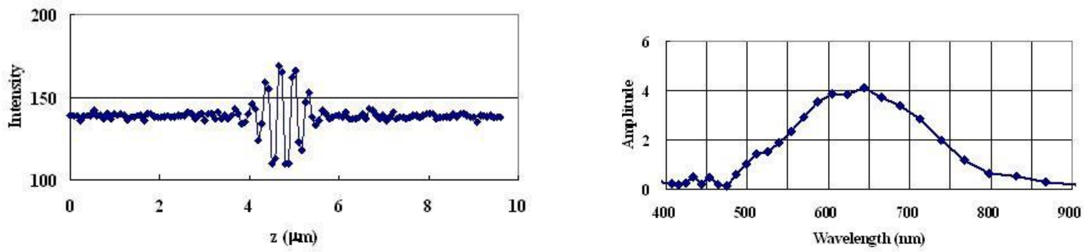
Fig. 3-1 White-light phase-shifting interferometry

3.3 Implementation

3.3.1 Equivalent wavelength and scan speed

In order to use the calculation formula of the conventional PSI method for phase calculation, the sampling point interval must be 1/4 cycle (corresponding to 90°) of the interferogram. Also, the equivalent wavelength is required when calculating the height from the phase using Eq. (3-1). However, since the illumination light used is white light, the wavelength cannot be specified. Therefore, the spectrum of the interference signal is obtained and its center wavelength is used as a representative value (called the equivalent wavelength).

The interferogram obtained by the experimental apparatus (surface profiler SP-500) and the wavelength spectrum obtained by Fourier transform are shown in Fig. 3-2. From this result, if the equivalent wavelength of white light is 640 nm, the interferogram period is 320 nm, the sampling point interval is 80 nm, and the scanning speed is 2.4 μm/s when using a 30 fps camera.



(a) (b)

Fig. 3-2 (a) Interferogram of white light interferometry. (b) Its spectrum.

3.3.2 Modulation peak position detection

There are many proposals for the peak position detection algorithm of the interferogram, such as the low-pass filter method. Here, one of the modulation calculation algorithms is used that uses the sampling point interval being 1/4 period (corresponding to 90°) of the waveform. The calculation algorithms have been proposed in parallel with the phase calculation algorithms of the conventional PSI method, and the typical modulation calculation formulas are shown in Table 3-1.

Table 3-1 Modulation calculation algorithms

Steps	Modulation	Reference
3	(1/2) sqrt[$(c\text{-}b)^2+(b\text{-}a)^2$]	Bhushan et al. 1985
4	(1/2) sqrt[$(b\text{-}d)^2+(c\text{-}a)^2$]	
5	(1/2) sqrt[$(b\text{-}d)^2-(a\text{-}c)(c\text{-}e)$]	Larkin et al. 1996
5	(1/4) sqrt[$4(b\text{-}d)^2+(\text{-}a+2c\text{-}e)^2$]	Hariharan et al. 1987
7	$(\text{-}a+3c\text{-}3e+g)/\sin\varphi$ or $2(\text{-}b+2d\text{-}f)/\cos\varphi$	Sandoz et al. 1997

Note: a, b, c, ⋯ are the intensity values.

Figure 3-3 shows the results of modulation calculation using some formulas. Modulation near the peak of intensity data g is calculated by the 4-point method, 5-point method (Larkin), and 5-point method (Hariharan). The 4-point method modulation is not smooth enough, but the 5-point method is sufficiently smooth. Based on the results of such comparative experiments, we adopted the 5-point method [Larkin et al. 1996], which has a low computational cost and stable calculation results.

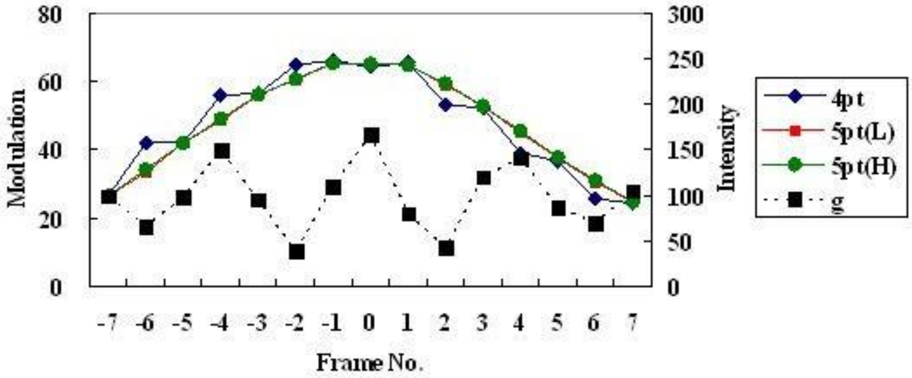


Fig. 3-3 Modulations calculated by various algorithms.

3.3.3 Phase calculation

The phase calculation uses the calculation formula of the conventional PSI method. Table 3-2 shows the typical phase calculation formulas when the phase shift is 90°.

Table 3-2 Phase calculation algorithms

Steps	φ = atan[ ]	Reference
3	$(-a+2b-c)/(c-a)$	Bhushan et al. 1985
4	$(b-d)/(c-a)$	
5	$2(b-d)/(-a+2c-e)$	Schwider et al. 1983, Hariharan et al. 1987
7	$(-a+3c-3e+g)/(2(-b+2d-f))$	Hibino et al. 1995
7	$(-a-4b+c+8d+e-4f-g)/(a-2b-7c+7e+2f-g)$	Zhang et al. 1999
9	$(-4b+12d-12f+4h)/(a-8c+14e-8g+i)$	Phillion 1997

Note: a, b, c, ⋯ are the intensity values.

Figure 3-4 shows the results of phase calculation using several formulas. This is the result of calculating the phase in the vicinity of the peak of the same intensity data g as in Fig. 3-3 by the 4-point method, 5-point method, and 7-point method (Hibino). Using this result, the height is calculated by Eq. (3-1) and the interference order is corrected. The result is shown in Fig. 3-5. Looking at the height stability near the modulation peak (frame number = 0), the 4-point method is unstable, and the 5-point and 7-point methods are stable with an error of 1 nm or less. Based on the results of such comparative experiments, the 7-point method [Hibino et al. 1995] was adopted. Please note that, in Fig. 3-5, the height inclines with increasing distance from the peak, and this is because the interferogram of white interference is not a simple cosine wave, as shown in Eq. (2-7).

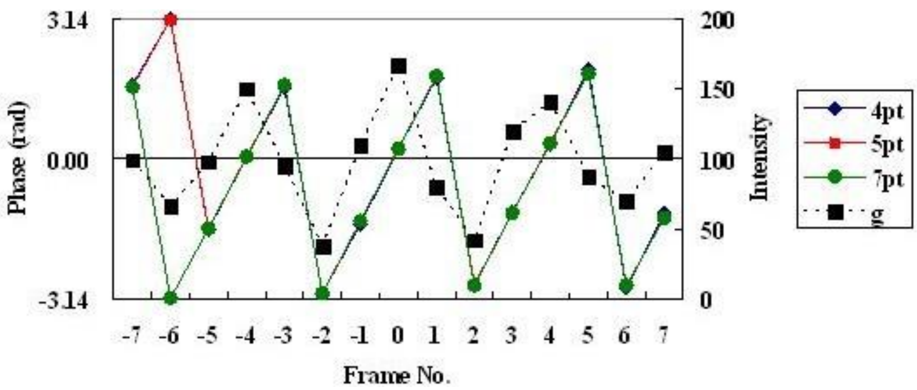


Fig. 3-4 Phases calculated by various algorithms.

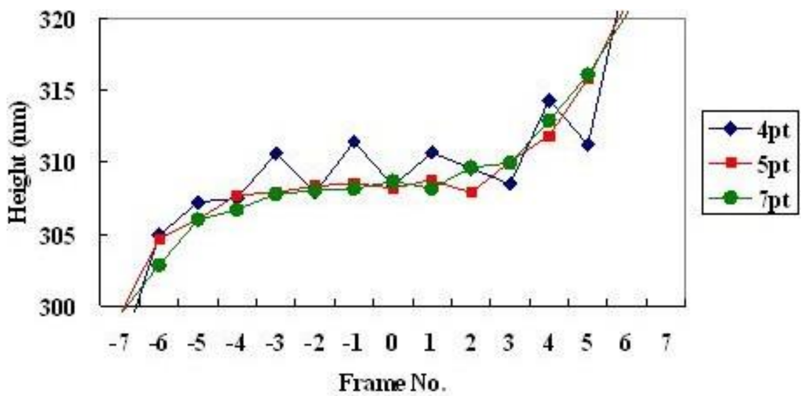


Fig. 3-5 Heights calculated by various algorithms.

3.3.4 Effect of phase change on sample surface reflection

When the surface to be measured is metal, the phase changes at the sample surface reflection. When the complex refractive index of the sample surface is $n-ik$, the amount of phase change is expressed by the following equation [Doi et al. 1992, The Japan Society of Mechanical Engineers 1996].

$$\phi = \mathrm{atan}\left(2k/(1-n^2-k^2)\right) \tag{3–2}$$

There are many reports on the effect of this phase change on surface profile measurement by optical interferometry, and it can be summarized as follows.

(1) When the target surface is homogeneous: only the overall height shifts, and there is no effect on shape measurement.

(2) When the target surface is not homogeneous:

(a) PSI method: due to the phase difference between dissimilar metals, an error of up to several tens of nm occurs [Doi et al. 1992].

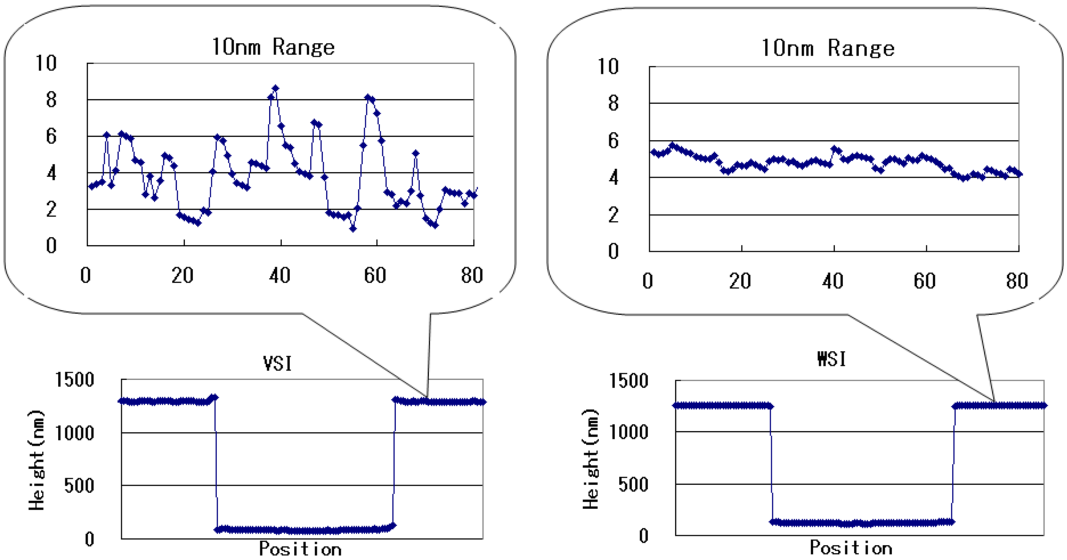
(b) VSI: the phenomenon is complicated because the wavelength dependence of the amount of phase change causes an error. The phase change is large and it is practically a problem in the case of metal, and an error of up to several tens of nm occurs [Park et al. 2000, Harasaki et al. 2001].

Based on experience in the industrial world, there is no need for measurement using white light interferometry to measure surface profiles of dissimilar materials with an accuracy of tens of nm. The PSI method is more suitable for this purpose. If there is a need for it, it will be necessary to measure and calibrate the surface covered with the same material by vapor deposition, etc. [1]. The study of the high-accuracy white light interferometry in this chapter aims to improve the measurement accuracy of the surface profile (for example, surface roughness) of the homogeneous material, and in practice, the phase change on the surface reflection does not pose a problem.

3.4 Experimental results

The algorithm in the previous section was implemented on the surface profiler SP-500 (Fig. 2-10), and the 1 μm standard step was measured by the VSI method and the WSI method. The results are shown in Fig. 3-6. The surface roughness of the WSI method is about 1/7 that of the conventional VSI method. The intensity data used are the same, and the superiority of the WSI algorithm is clear. In addition, the measurement reproducibility of 1 μm step is 0.91 nm, which is the highest level in the industry.

Table 3-3 compares the conventional method and the WSI method. The WSI method approaches the accuracy of the PSI method while maintaining the versatility of the VSI method.



(a) Results by VSI method (b) Results by WSI method

Fig. 3-6 Comparison of measurement results

[1] The height measurement of the white light interferometry depends on the displacement sensor (for example, capacitance sensor) built in the vertical scanning mechanism, so some calibration is necessary. Standard steps are used for normal calibration. A method of incorporating a high-precision laser displacement meter has also been proposed [Doi and Kurosawa 2002, Schmit et al. 2002]. In principle, it is different from the PSI method which uses the wavelength of light as a ruler.

Table 3-3　Comparison of three methods

Item	VSI	PSI	WSI
Illumination	White	Monochromatic	White
Principle	Peak	Phase	Peak & Phase
Target surface	General	Smooth only	General *)
Accuracy	Low (ca. a few nm)	Best (ca. 0.01 nm)	High (ca. 1 nm)
Scan speed	Arbitrary	−	2.4 μm/s
Meas. speed	Slow	High	Middle

*) Outlier occurrence on a rough surface (See Section 3.5)

3.5 Outlier occurrence and its phenomenon analysis

When various samples were measured by the proposed method, the abnormal values shown in Fig. 3-7 were encountered. This sample is a machined surface of metal (stainless steel) and has lateral machining marks as shown in Fig. 3-8. Dozens of points on this surface contain spike noise of about 300 nm (corresponding to one cycle of the interferogram). Such an abnormal value occurs because the envelope peak in the WSI algorithm is detected with a wavelength shift, and is a so-called “wavelength jump” phenomenon.

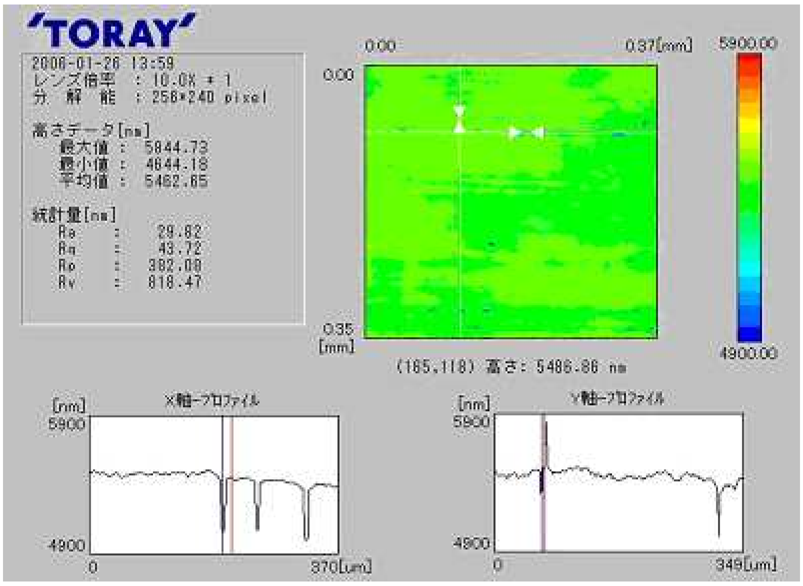


Fig. 3-7　Spike noises in a metal surface measurement

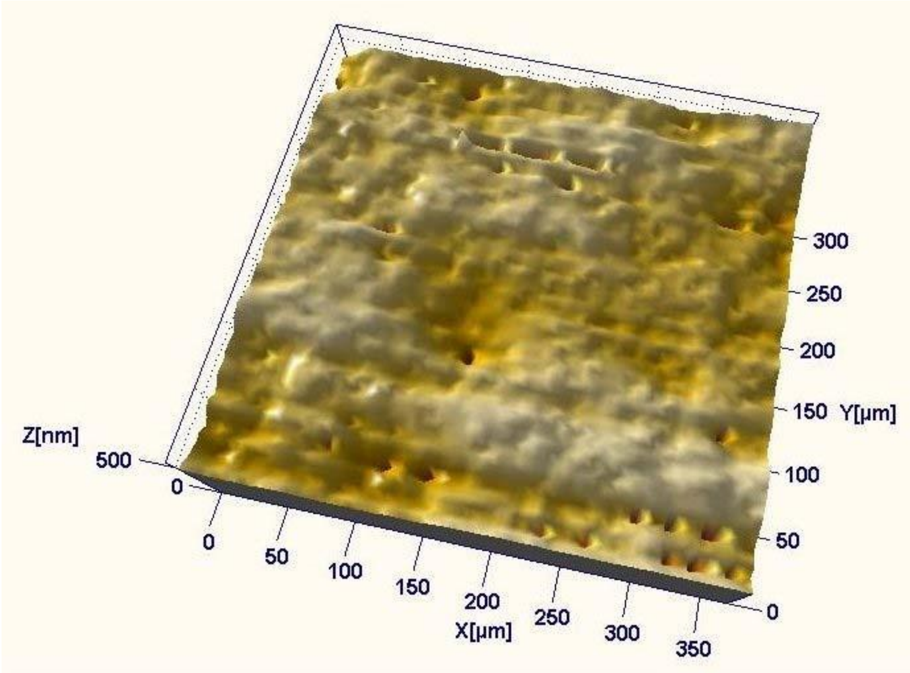


Fig. 3-8 Spike noises in a metal surface measurement (3D view)

In order to analyze this phenomenon, a comparison of interferograms near the outliers is shown in Fig. 3-9. This figure plots a total of 10 interferograms at 2-pixel intervals in the y direction on the image. The vertical axis is intensity, but the base is shifted for easy viewing. There are two abnormal points, y=429 and y=431, and the height is about 5070 nm, which is lower than other points. Looking at the waveform, it can be seen that the two maximum peaks are shifted to the left by one.

When the interferogram of such abnormal points is enlarged, it is as shown in Fig. 3-10, and the maximum modulation point has a downward peak. The conventional VSI algorithm that detects the peak position of the envelope has little effect on the height estimation value, but the algorithm that considers the phase, such as the proposed method, causes wavelength jumping and the problem becomes obvious.

This phenomenon hardly occurs on smooth surfaces such as glass or mirror surfaces of wafers, and is often present on rough surfaces such as metal working surfaces. There is a report that its cause is the modulation and phase offset phenomenon [Rhee et al. 2005], but the original cause has not been clarified.

Therefore, we decided to use the proposed method only when the measurement target is a smooth surface. It is also effective to apply a median filter to the measurement results to remove scattered noise.

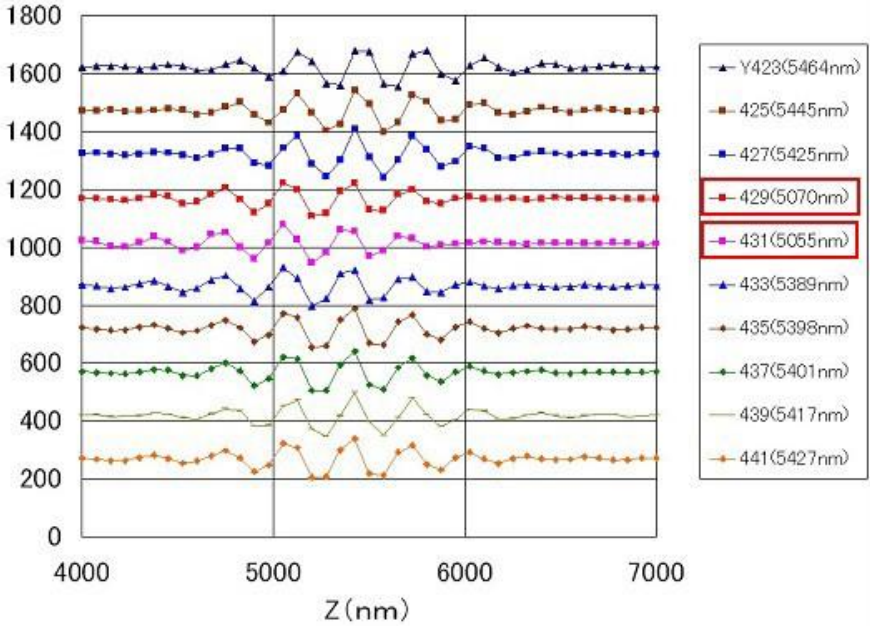


Fig. 3-9 Comparison of interferograms

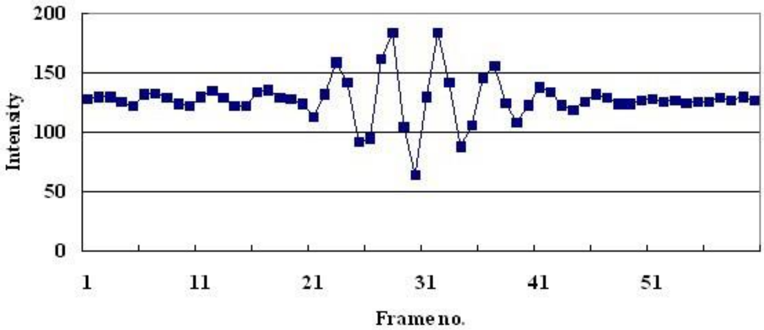


Fig. 3-10 Abnormal interferogram observed in a rough surface measurement

3.6 Summary

In order to improve the measurement accuracy of the white light interferometry, we proposed an algorithm that uses the phase information (named WSI method). The equivalent wavelength is obtained from the spectrum of the interferogram, and the scanning speed is determined based on this wavelength. The approximate height is calculated from the image number where the modulation peaks, and the height is corrected using the phase calculated from the intensity data in the vicinity. From an experiment using a surface profiler incorporating this algorithm, we obtained a measurement reproducibility (σ) of 0.91 nm for a 1 μm step. This is about 7 times more accurate than the VSI method, and the accuracy can be improved without increasing the calculation time. However, when the target is a rough surface, wavelength jump noise was observed, and it was clarified that it comes from the modulation and phase offset phenomenon.

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