Research and Simulation of Negative Group Delay and Superluminal Propagation

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***Abstract*—In recent years, negative group delay circuits have attracted much attention due to their propagation characteristics and wide application prospects. In the history of human exploration, the exploration of the speed of light has never stopped. The theory of relativity points out that the speed of light in vacuum is the limit speed of signal propagation. However, it is found through research that phase velocity and group velocity appear faster than the speed of light, which does not violate the causal relationship. This paper first introduces the related concepts of negative group delay and superluminal phenomenon, the second focuses on the principle of negative group delay and superluminal phenomenon in-depth analysis and research, finally using the principle of Multisim software, the bandwidth of two different job, different structure of circuit design, the virtual simulation experiment to negative group delay phenomenon and measurement data. It is of great significance to explore the field of faster-than-light and negative group delay in today's rapidly developing information age, and it can try to meet the high requirements for signal transmission. In the future, the interdisciplinary research direction of this research topic also has great development space.**

Keywords-Superluminal Phenomenon; Phase Velocity; Group Velocity; Signal Transmission; Simulation Study

I. INTRODUCTION

For a long time, most of the research on linear signal transmission system focuses on amplitude-frequency response, but pays less attention to phase-frequency response. In recent years, with the development of communication and space detection, the transmission capacity and channel transmission characteristics of signals are increasingly demanding. Scholars have found that compared with the information transmission of amplitude in the process of signal transmission, the phase can carry more useful information with higher stability, and group delay is a very important parameter. The study of group delay and superluminal speed is of great significance in space testing, navigation system, military positioning and so on.

Sommerfeld and L. Brillouin discovered the negative wave velocity in classical electromagnetic wave theory, and pointed out that in the irregular dispersion region, the group velocity can exceed the speed of light in vacuum, and can even be negative. At present, there are two main directions in the research of "superluminal physics". One is the superluminal phenomenon realized by particles through

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anti-dispersion regulation, and the other is the superluminal phenomenon realized by electronic circuits. Human's exploration and measurement of the speed of light can be traced back to 1607, when Italian scientist Galileo Gallei put forward the scientific idea that "the speed of light is finite" [1], although his attempt was unsuccessful. In 1907, Einstein discussed the concepts of negative group velocity and negative time. In 1970 G. Garrett and D. Mc Dumber showed that faster-than-light group velocities and even negative group velocities could be observed experimentally while keeping the pulses undistorted. N. Budko et al. discovered negative wave velocities in 2009 while studying the near-field region of an antenna (source), with some waveforms showing retrograde to time. In 2011 Liang Zhang et al. observed a time advance of 221.2ns before the input signal. Hyper-luminal physics can be tested in two broad categories, namely hyper-luminal phenomena of particles regulated by anomalous dispersion and negative group velocity phenomena in electronic circuits, of which negative group velocity accounts for about half. The research of superluminal speed in China began roughly in the 1980s.In 1984, Tan Xue sheng put forward the standard space-time theory, which allows the existence of superluminal motion without violating the theory of causality. In 2003, Huang Zhixun et al. completed group velocity hyper-luminal experiment at shortwave, which was the first hyper-luminal experiment in China. Meanwhile, in 2002, Liu Liao pointed out that the negative velocity means that the delayed light pulse becomes the advanced light pulse, which challenges the absoluteness of the time sequence of causality and also has an impact on relativity. Up to now, the study of superluminal physics has a short history and its development is not yet mature, but it has already taken preliminary shape. As a newly emerging science with promising signs, its vitality and development potential is obvious and very necessary. For example, in 2012, the United States Space Administration (NASA) organized the "Star-ship Centennial Symposium", in which the so-called warp propulsion of the superluminal universe solution was discussed; In recent years, many Chinese scientists have joined in the field of faster-than-light research and made contributions. In 2019, Xia Hualing is the first person to utilize the fidelity concept in quantum mechanics to define the signal integrity of the signal through the dispersion circuit, and is the first person to apply the cascaded dual-band electronic amplification circuit to obtain abnormal dispersion region, and systematically proves that fidelity change in normal and abnormal dispersion cascaded electronic circuit depends on different truncation parameters or pulse shape on the electrical signal [8].

In this paper, the definition of phase velocity and group velocity is introduced, and the idea of group velocity exceeding the speed of light is in line with relativity is proved by quantum hypothesis and wave dispersion relationship. At the same time, the production mechanism of negative group delay and circuit characteristics are elaborated in detail. A virtual simulation experiment is carried out. Two kinds of electronic circuits of high frequency band and low frequency band are used to measure the pulse results by using Multisim simulation software. The results are consistent with the theoretical calculation. It is of great significance to explore the field of superluminal speed and negative group delay in today's rapidly developing information age, so we can try to meet the high requirements of signal transmission.

II. APPLICAIOTN SCENARIOS

A. Concepts related to superluminal velocities

In the vibration and wave of the optical part of physics, the two basic physical quantities, phase velocity and group velocity, play an important role in the related research and exploration.

Phase velocity refers to the phase moving velocity or phase velocity of a wave, or phase velocity for short. Phase velocity is defined as the advancing velocity of a constant phase point of an electromagnetic wave [2].In other words, this is the speed at which the wave will transmit the phase that any frequency component has. In which the electric field is:

$$E\left(z,t\right) = E_m \cos\left(\omega t - \beta z\right) \tag{1}$$

The phase velocity of electromagnetic wave shall be:

$$\upsilon_p = \frac{dz}{dt} = \frac{\omega}{\beta} \tag{2}$$

Where beta is the phase constant, which determines whether the phase velocity is dependent on frequency.

The group velocity is the advancing velocity of an envelope wave at a constant phase point. In a complex or modulated signal, there are thousands of frequency components, and a simple phase velocity cannot accurately describe the propagation speed of a signal. The transmission of the signal depends on the modulation of the wave, and the speed of the modulated wave is the speed of the signal transmission. Given two traveling waves with both amplitudes, they can be expressed as E_m :

$$E_1 = E_m e^{j(\omega+\Delta\omega)t} e^{-j\left(\beta+\Delta\beta\right)z} \tag{3}$$

$$E_2 = E_m e^{j(\omega-\Delta\omega)t} e^{-j\left(\beta-\Delta\beta\right)z} \tag{4}$$

Where, $\omega+\Delta\omega$ and $\omega-\Delta\omega(\Delta\omega << \omega)$ is the angular frequency, $\beta+\Delta\beta$ and $\beta-\Delta\beta$ is the phase constant.

Then the resultant wave of the two traveling waves is

$$E = E_1 + E_2 = 2E_m \cos(\Delta\omega t - \Delta\beta z)e^{j(\omega t-\beta z)} \tag{5}$$

It is concluded that the amplitude of the synthesized wave is modulated, which is called envelope wave， where C is a constant.

$$\Delta\omega t - \Delta\beta z = C \tag{6}$$

The group velocity is defined as

$$\upsilon_g = \frac{dz}{dt} = \frac{\Delta\omega}{\Delta\beta} \xrightarrow{\Delta\omega<<\omega} \upsilon_g = \frac{d\omega}{d\beta} \tag{7}$$

The trigonometric part of equation (5) can be approximated as the envelope signal, and the difference in peak time between the output pulse and the input pulse is determined by the maximum value of the envelope of the output pulse and the input pulse [8]. When the output pulse distortion is small, the time delay of the envelope peak can be approximately viewed as the group time delay of the pulse. Theoretically, we know that the group delay is determined by the derivation of the phase over-frequency on the pulse carrier frequency, but due to the finite width of the pulse spectrum, the actual group delay is slightly different from the theoretical prediction.

B. Group velocities exceeding the speed of light are relativistic

In 1905, Einstein put forward the light quantum hypothesis, which explained the photoelectric effect more accurately, and won the Noble Prize in Physics in 1921.In 1904, de Broglie proposed that physical particles also have waves. He used analogy to make the wave-particle duality of light no longer limited to particles and quanta, but extended to general matter particles [10]. In quantum mechanics, it is called matter wave theory, also known as "de Broglie matter wave theory", where the relationship between energy E, momentum p, frequency ν , wavelength λ and Planck constant h:

$$\lambda = \frac{h}{p} \tag{8}$$

$$\nu = \frac{E}{h} \tag{9}$$

According to Einstein's mass-energy formula:

$$E = mc^2 \tag{10}$$

Arrive at:

$$\upsilon_p = \lambda \cdot f = \frac{h}{m\upsilon} \cdot \frac{mc^2}{h} = \frac{c^2}{\upsilon} \tag{11}$$

Where υ_p is the de Broglie wave phase velocity, is the particle velocity υ:

$$\upsilon_g = \frac{d\omega}{dk} = \frac{d\ \ h\omega}{d\ \ hk} = \frac{dE}{dp} \quad (12)$$

Where υ_g is the group velocity, and according to the relationship between energy and the momentum:

$$\upsilon_g = \frac{dE}{dp} = \frac{p}{m} = \upsilon \quad (13)$$

That is, the particle velocity is equal to the group velocity, and then there is

$$\upsilon_g \upsilon_p = c^2 \quad (14)$$

Einstein's special theory of relativity has mentioned a very important idea: the speed of light cannot be exceeded, that is, the speed of particles must be less than the speed of light, so it can be deduced. $\upsilon < \upsilon_p$ $\upsilon_p > c$ In other words, the de Broglie wave phase velocity can exceed the speed of light. Doesn't the de Broglie wave phase velocity faster-than-light violate special relativity? The fact is that the phase velocity super-lumen was discovered in the early days of Einstein's theory of relativity, but he did not think that the phase velocity super-lumen would affect the relatively sound theory of relativity, because a monochromatic wave with constant frequency cannot transmit information, and the phase velocity refers to the speed at which a monochromatic wave with constant frequency travels [3]. In order to transmit information, A slower-changing wave packet needs to be modulated onto a sinusoidal wave [6], and the propagation speed of such a packet is called the group velocity. Whether the phase velocity and the group velocity can travel faster than the speed of light actually depends on the dispersion relationship of the medium through which the wave travels. In anomalously dispersive media, the group velocity of waves can also exceed the speed of light [7].For the analysis of dispersion, according to the definitions of group velocity and phase velocity derived above:

$$\upsilon_g = \frac{dz}{dt} = \frac{\Delta\omega}{\Delta\beta} \quad (15)$$

$$\upsilon_p = \frac{dz}{dt} = \frac{\omega}{\beta} \quad (16)$$

The relationship between group velocity and phase velocity can be obtained:

$$\upsilon_g = \frac{d\omega}{d\beta} = \frac{d\ \ \upsilon_p\beta}{d\beta} = \upsilon_p + \frac{\omega}{\upsilon_p} \cdot \frac{d\upsilon_p}{d\omega}\upsilon_g \quad (17)$$

It follows that:

$$\upsilon_g = \frac{\upsilon_p}{1 - \frac{\omega}{\upsilon_p}\frac{d\upsilon_p}{d\omega}} \quad (18)$$

As can be seen from the above equation, group velocity and phase velocity are not equal in general, and the classification discussion is as follows:

a) No dispersion: if the group velocity is equal to the phase velocity, $\frac{d\upsilon_p}{d\omega} = 0$, then the phase velocity is independent of the frequency;

b) Normal dispersion: if the group velocity is less than the phase velocity, $\frac{d\upsilon_p}{d\omega} < 0$, the phase velocity is inversely proportional to the frequency;

c) Abnormal dispersion: if the group velocity is greater than the phase velocity, $\frac{d\upsilon_p}{d\omega} > 0$, the phase velocity is proportional to the frequency..

According to the above analysis of the dispersion of the relationship between the physical quantities. Related, there is the Cherenkov effect refers to the speed of light in a medium is smaller than the speed of light in a vacuum, particles in the medium may travel faster than the speed of light in the medium, in which case radiation will occur. But that's not really superluminal, which is superluminal in the sense of exceeding the speed of light in a vacuum.

III. Concepts and Mechanisms Related to Negative Group Delay

A. Negative group delay

The group velocity representing the transmission speed of the envelope signal in the medium can be expressed as:

$$\upsilon_g(\omega) = \frac{c}{n_g(\omega)} \tag{19}$$

Where, ω is the angular frequency, c is the speed of light in vacuum, and n_g is the group refractive index.

Therefore, the group time delay required for electromagnetic wave to pass through a medium of length z can be expressed as:

$$\tau_g(\omega) = \frac{z}{\upsilon_g(\omega)} = \frac{z n_g(\omega)}{c} = \tau_c n_g(\omega) \tag{20}$$

Where, $\tau_c = \frac{z}{c}$ is the transmission delay of light in a vacuum of length z.

According to the above two formulas, electromagnetic wave transmission in the medium has the following three conditions:

a) $n_g > 1$, the group velocity of the wave is less than the speed of light, $\upsilon_g < c$, $\tau_g < \tau_c$, τ_g is positive;

b) $0 < n_g < 1$, the wave group velocity exceeds the speed of light, $\upsilon_g > c$, $\tau_g < \tau_c$, τ_g is positive;

c) $n_g < 0$, then the group velocity of the wave is negative, and $\upsilon_g < 0$, $\tau_g < \tau_c$, τ_g is negative.

The above three cases can be shown in Figure 1, the Curves A, B and C in the figure correspond to cases a), b) and c) respectively. According to the above analysis and Figure 1, negative group velocity and exceeding the speed of light both mean that the transmission delay of envelope signals in medium is smaller than that in vacuum, namely the so-called "super-lumen phenomenon" [9]. However, different from the superluminal group velocity, negative group delay also means that the output envelope peak appears earlier than the input envelope, which is a strange phenomenon.

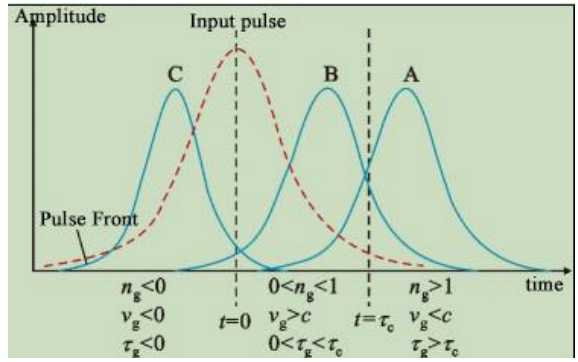

Figure. 1. Group refractive index, group velocity, group delay and the relationship between the speed of light

A. Negative group delay generation mechanism and circuit characteristics

Negative group delay phenomenon is essentially due to the abnormal dispersion characteristics of the medium. [4] Bolda et al. were the first to theoretically prove that the phenomenon of negative group delay in dispersive media occurs at the extremum of wave attenuation.

The difference between the transmission group delay defined in a medium of length z and the group delay in a vacuum is:

$$\Delta\tau(\omega) = \tau_g(\omega) - \tau_c = \left(\frac{1}{\upsilon_g} - \frac{1}{c}\right) \cdot z \tag{21}$$

Using the properties of analytic functions, it can be proved that:

$$\Delta\tau(\omega) = \frac{z}{\pi} P \int_{-\infty}^{+\infty} \frac{k(\tilde{\omega}) - k(\omega) - (\tilde{\omega} - \omega)\frac{dk(\omega)}{d\omega}}{(\tilde{\omega} - \omega)^2} d\tilde{\omega} \tag{22}$$

Where P is the Cauchy principal value and $k(\omega)$ is the imaginary part of the wave number. In the above equation, if $\frac{dk(\omega)}{d\omega} = 0$, the maximum or minimum value of $k(\omega)$ is taken, the corresponding integral result is negative or positive. Since $k(\omega)$ represents the absorption attenuation of the wave, there is at the attenuation maximum, $\Delta\tau(\omega) < 0$, indicating that the group velocity in the medium is greater than the speed of light or is negative. This proof not only shows the condition for the existence of negative group delay, but also shows the relationship between negative group delay and amplitude response. At present, most negative group delay circuits rely on energy resonance or coupling to generate negative group delay and have obvious amplitude attenuation extremum characteristics, which is consistent with the above proof conclusions.

B. The relationship between negative group delay and superluminal speed

When we consider a system, it is easy to understand that supports a vacuum path (length L) and a lumped system (delay t_d), which is located at the end of the path [11]. The total time requires a pulse to pass through this system:

$$t_{total} = \frac{L}{c} + t_d \tag{23}$$

The corresponding total speed $\upsilon_g = \frac{L}{t}$ satisfies the relation:

$$\frac{1}{\upsilon_g} = \frac{1}{c} + \frac{t_d}{L} \tag{24}$$

For $\upsilon_g < c$ (positive delay) and $t_d < 0$ (negative delay), there are two cases. In $-t_d < \frac{L}{c}$ case, υ_g greater than c (in the narrow sense of superluminal), while in $-t_d > \frac{L}{c}$, υ_g becomes negative (negative group velocity). In the latter case, the lumped part's contribution is superior to the free propagation path.

In general, superluminal is considered a propagation effect [15] But in many cases, it seems more appropriate to discuss the negative group delay of a lumped system. We take experimental parameters from it, where we observe a negative delay of 60ns.We note that the pulse length $cTw = c \times 2\mu s = 600m$ is much longer than the cell length L = 6 cm long [14]. Therefore, we can safely use the lumped approximation. Since we can eliminate the carrier frequency with a slowly changing envelope approximation, the wavelength of light will no longer come into play. It should be emphasized that the second term in the equation.(4) or (5), whether it is positive or negative, dominates the first term. For typical atomic experiments, the bandwidth $\Delta\omega$, from MHz to GHz, roughly determines, $|t_d| \sim \frac{\Delta nk0L}{\Delta\omega} \sim \frac{1}{\Delta\omega}$, µs to ns, while the passage time is less than of ns. In this case, forcing a speed to be assigned, as in the example above, $\upsilon_g = -1/300\ c$, will cause some confusion [12].

We try to design a simple circuit to carry out a virtual simulation experiment to realize this phenomenon, to explore further.

IV. THEORETICAL CALCULATION AND SIMULATION EXPERIMENT

A. Circuit characteristic description and measurement method

Signals can be expressed in the time domain and frequency domain, and the effects corresponding to the circuit can also be described in the time domain and frequency domain. The field of group delay focuses on the change of signals in the frequency domain, so only the transfer function of the circuit and its related amplitude response, amplitude Angle response, and group delay need to be considered. The corresponding relation derived from the transfer function is shown as follows:

$$V_{out}(\omega) = H(\omega)V_{in}(\omega) \tag{25}$$

$$H(\omega) = \frac{V_{out}}{V_{in}} \tag{26}$$

The transfer function can be expressed in a complex form, namely:

$$H(\omega) = a + ib \tag{27}$$

Where a and b are represented as the real part and the imaginary part respectively, and at least one of them contains variables. From this, the amplitude response and amplitude angular response of the transfer function are:

$$A(\omega) = |H(\omega)| = \sqrt{a^2 + b^2} \quad (28)$$

$$\phi(\omega) = \arg[H(\omega)] = \arctan(\frac{b}{a}) \quad (29)$$

The group delay is the derivative of the angular response with respect to the angular frequency and takes a negative value. When the angular frequency is determined, the group delay also has a fixed value:

$$t_d = -\left.\frac{d\phi(\omega)}{d\omega}\right|_{\omega_0} \quad (30)$$

In an ideal state, the amplitude response is expected to be 1, so that the pulse does not deform, and the group delay can be fixed if the amplitude angular response is linear with respect to the angular frequency [16].

In the measurement of the circuit, there are two kinds of measurement: sinusoidal pulse measurement and modulated pulse measurement.

According to the description of the group velocity theory above, the group delay in envelope signals is represented by the change of the envelope peak. The input and output pulses are placed on the same time axis for comparison, and the time delay time can be obtained by comparing the position of the envelope peak on the time axis. Therefore for a modulated pulse, the group delay value can be directly obtained by comparing the peak value of its envelope signal [13].

In addition to the modulation pulse measurement, a single sinusoidal pulse (analogous to the monochromatic light dispersion effect) can also be measured. At this time, the phase shift of the pulse, namely the amplitude Angle response, can be obtained directly from the time axis, while the group delay needs to continue to be derived by its derivative. This measurement method can be used to conduct experiments from the theoretical reasoning sequence, analyze the experimental principle, but also more convenient for the measurement of low-frequency working bandwidth circuit.

A. Theoretical calculation results

In this experiment, two kinds of circuits are selected for analysis and testing. They correspond to the working bandwidth of low frequency band and high frequency band.

a) Low frequency RC loop

The working circuit of low frequency band consists of an amplifier and two groups of resistors and capacitors. The circuit diagram is shown in Figure 2. As shown in the Figure of the paper [11].

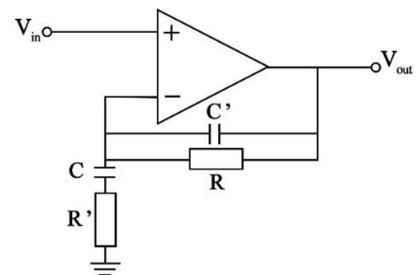

Figure. 2. Low frequency circuit

The transfer function of this circuit is:

$$H_{low}(\omega) = 1 + \frac{i\omega RC}{(1+i\omega R'C)(1+i\omega RC')} \quad (31)$$

After appropriate parameters are selected, the corresponding amplitude response, amplitude angular response and group delay relationship can be obtained as shown in FIG. 3, 4 and 5, where the green line represents the ideal condition, and the yellow line represents the actual theoretical data of the circuit. It can be found that the negative group delay phenomenon of the circuit is mainly in the low frequency band, and each data is symmetric relative to the frequency of 0Hz. Although the frequency less than zero is meaningless. When working in low frequency bands, the lower the frequency, the greater the negative group delay, and there is no longer a negative group delay phenomenon around 10Hz.

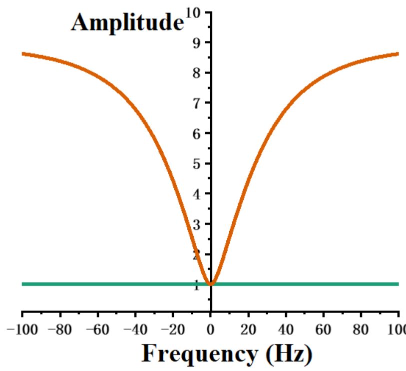

Figure. 3. Theoretical curve of amplitude response of low frequency circuit

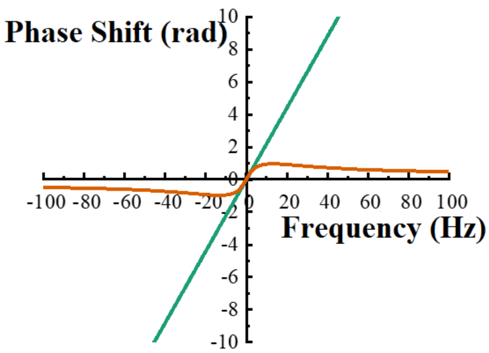

Figure. 4. Theoretical curve of amplitude-angle response of low-frequency circuits

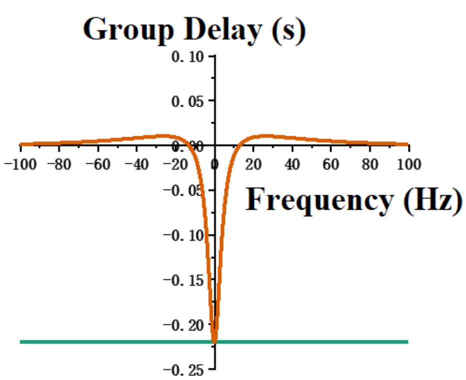

Figure. 5. Theoretical delay curve of low-frequency circuit groups

b) High band RLC loop

A circuit that realizes the phenomenon of negative group delay in high frequency band increases the use of inductors compared to low frequency circuits, and the transfer function of this circuit is relatively more complex. The first-order circuit diagram and its transfer function are shown in Figure 6, Eq. (32) and (33), while the second-order circuit diagram and its transfer function are shown in Figure 7, Eq. (34), (35) and (36).

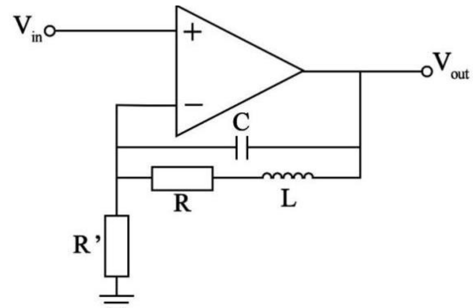

Figure. 6. First-order high-frequency circuit

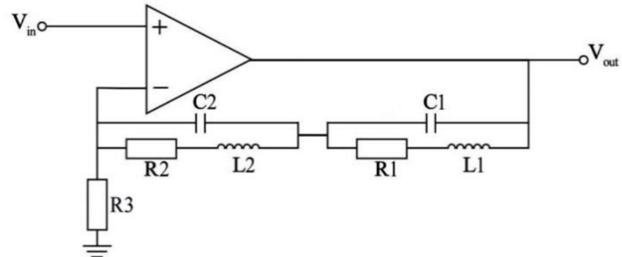

Figure. 7. Second order high frequency circuit

$$H_{high}(\omega)=1+\frac{Z}{R'} \tag{32}$$

$$Z=\frac{1}{i\omega C+\frac{1}{R+i\omega L}} \tag{33}$$

$$H_{high}(\omega)=1+\frac{Z_1+Z_2}{R_3} \tag{34}$$

$$Z_1=\frac{1}{i\omega C_1+\frac{1}{R_1+i\omega L_1}} \tag{35}$$

$$Z_2=\frac{1}{i\omega C_2+\frac{1}{R_2+i\omega L_2}} \tag{36}$$

In the same way, appropriate parameters of electronic components are selected to draw the relationship diagram of amplitude response, amplitude Angle response and group delay, as shown in FIG. 8, 9 and 10, where the red curve is the characteristic curve of first-order circuit, and the green curve is the curve of second-order circuit. The operating range of this circuit is at high frequency, so it does not need to consider the situation around zero point, so it does not consider the negative frequency range of the image. Yellow represents the theoretical data of the actual circuit. Due to the polymorphism of this circuit, the linear ideal state of the phase shift and group delay part is no longer of reference significance, but the ideal amplitude is still expected to be approximately 1. It has a very different performance from the low-band circuit, and the maximum negative group delay point is roughly 23kHz and 36kHz position, there are two points.

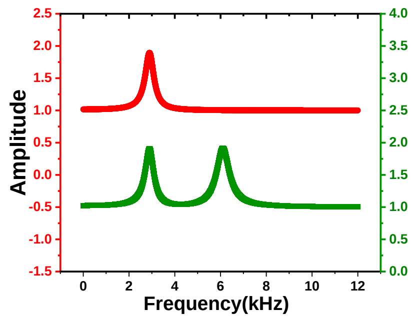

Figure. 8. Theoretical curve of amplitude response of high frequency circuit

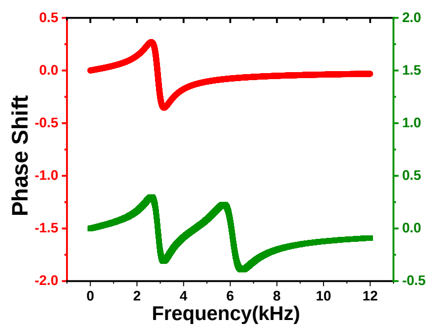

Figure. 9. Ideal amplitude-angle response curve of high frequency circuit

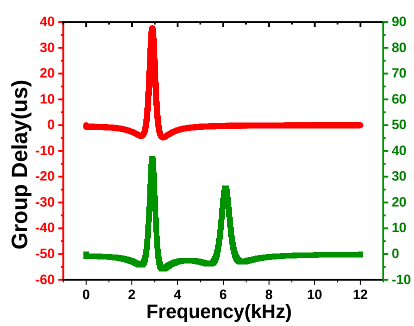

Figure. 10. Ideal delay curve of high frequency circuit group

B. Simulation test

Multisim simulation software is selected for simulation test. The software has the function of simulating various components, which can choose whether to produce noise or not. The built-in function generator and oscilloscope also meet the experimental requirements. In this study, sinusoidal pulse and modulated pulse are used as output pulses, and experiments are carried out in both low frequency and high frequency circuits. The low frequency circuit tests sine and modulation. The first order high frequency circuit tests the modulated pulse, and the second order high frequency circuit tests the sinusoidal pulse.

a) Low frequency circuit test

Figure. 11 shows the construction of the low-frequency working circuit in the simulation software, Figure. 12 is the screenshot of the 0.5Hz sinusoidal pulse used for testing, and Figure. 13 is the 1Hz carrier modulated pulse used as the simulation result of the test signal, where red is the input pulse and green is the output pulse. It can be found that the sinusoidal pulse has obvious phase shift phenomenon, and the envelope group delay phenomenon of the modulated pulse is also obvious.

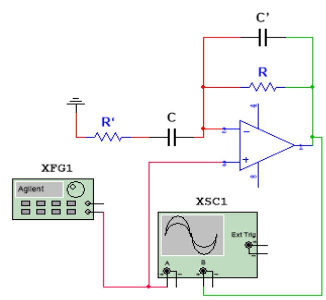

Figure. 11. Low frequency working circuit in Multisim analog system

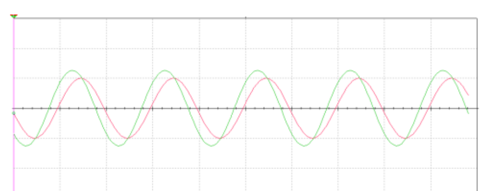

Figure. 12. Test result of sinusoidal pulse of certain frequency in low frequency circuit

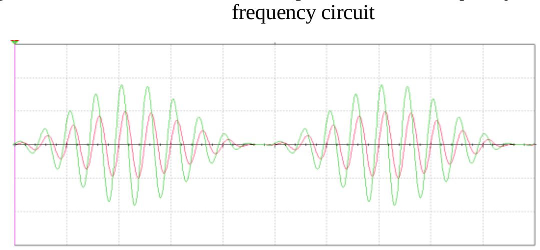

Figure. 13. Test results of a frequency modulation pulse of a low frequency circuit

Simulation software is used to measure the pulse conditions under different pulses and measure the relevant data, and compare with the theoretical data.

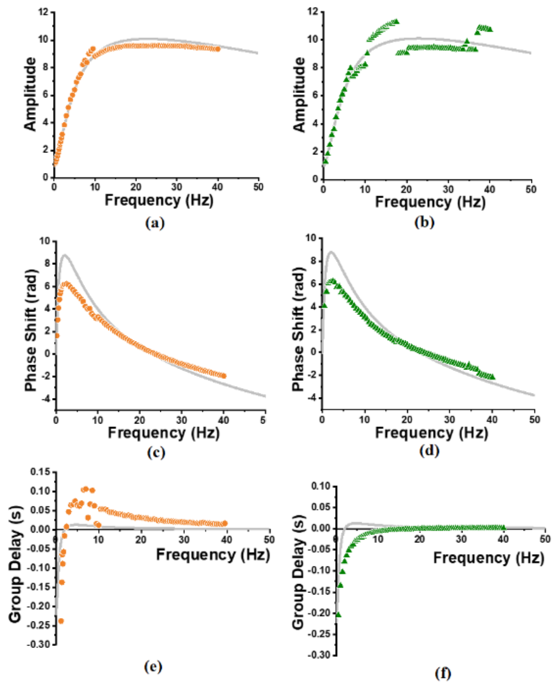

Figure. 14. Low frequency circuit test results

Measured from 0Hz to 40Hz, the group delay under each measurement frequency was obtained, and compared with the theory, plotted in FIG. 14, where the gray curve is the theoretical curve, the orange dot is the sinusoidal pulse test result, and the green triangle is the modulation pulse test result. (a) and (b) represent amplitude conditions, (c) and (d) represent phase shift conditions, and (e) and (f) represent group delay conditions. Through analysis, it can be found that the overall data trend is in line with the theoretical reasoning, and the error is also within the acceptable range. The main reasons for the errors are the sampling rate of the test software (affecting the program fitting) and the influence of the test frequency step size (especially the sine pulse needs to be differentiated).

b) High frequency circuit test

The test of high-frequency circuit shows the input and output of sinusoidal pulse and modulated pulse in the simulation software, in which the gray curve is the theoretical curve, the green triangle is the modulation pulse test first-order high-frequency RLC amplifier circuit, and the orange dot is the sinusoidal pulse test second-order high-frequency RLC amplifier circuit. Select some feature points in 0Hz-80000Hz for testing. Due to the sampling accuracy, test frequency compensation, fitting error and other problems, there are some errors, the final test results are in line with the theoretical situation on the whole.

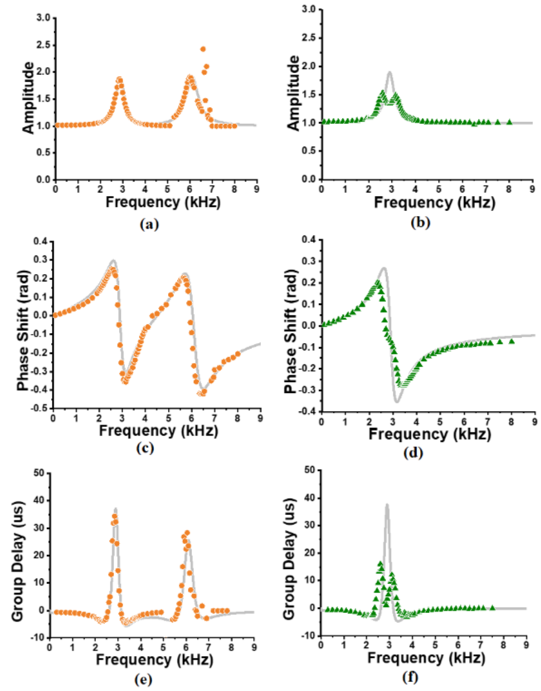

Figure. 15. Test results of high frequency circuit

When we used the Multisim simulation software for simulation test, the problem of image "breakdown" occurred many times, which was manifested as interruption of the output pulse curve, as shown in Figure 16. The reason was that the chip voltage was not enough to support or was related to frequency distortion. When the input signal of the amplifier circuit is a multi-frequency signal, if the amplifier circuit has different gain amplitudes for different frequency components of the signal, it will lead to distortion of the output waveform, which is called amplitude distortion; If the relative phase shift changes, it is called phase distortion, and the two are collectively referred o as frequency distortion. Frequency distortion is caused by the linear reactance element of the circuit, and frequency distortion is characterized by the absence of new frequency components in the output signal that are not present in the input signal.

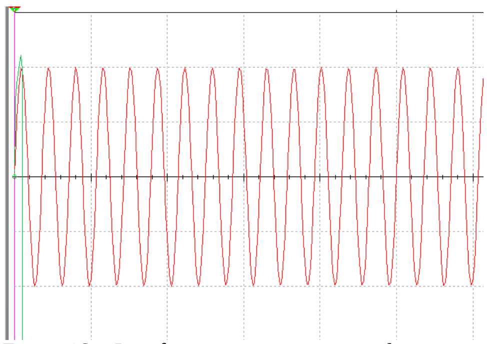

Figure. 16. Low frequency circuit output pulse interrupt

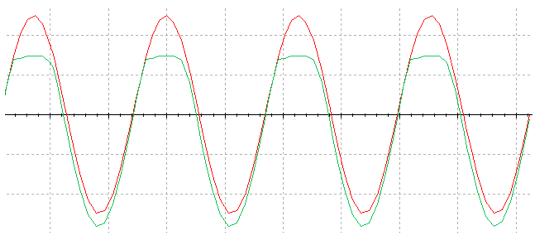

Figure. 17. Low frequency circuit pulse peak missing

In the simulation operation, the simplest way to solve this problem is to lower the input pulse amplitude. Then by adjusting the scale of the channel to flexibly control the view window to observe whether the output pulse is complete, if the output pulse waveform is complete, but the shape near the peak is obviously "decapitated", you need to continue to adjust the input pulse amplitude, until the input and output pulse are intact can continue to complete the experiment.

V. CONCLUSION

In this paper, the concepts of negative group delay and superluminal phenomenon are introduced. By using the principle and simulation test of RC negative group delay circuit, the superluminal phenomenon under negative group delay can be realized. In this paper, the principle of negative group delay and super-lumen phenomenon is analyzed and elaborated, so as to explore the negative group delay related technology at a higher level. Finally, through the simulation test of electronic circuit, the expected results are obtained. In the follow-up research work, we will continue to carry out theoretical exploration, plan better test methods, try more component parameters to meet more working bandwidth, and further in-depth study on negative group delay and super-lumen. The exploration and research of superluminal and negative group delay is of great significance in today's rapidly developing information age. In recent years, with the development of communication and space exploration, the transmission capacity and channel transmission characteristics of signals are increasingly required. Group delay is a very important parameter in the process of signal transmission. The study of group delay and superluminal speed is of great significance in space testing, navigation system, military positioning and so on.

There are many possibilities in the field of negative group velocity research. It is not a single discipline study, but a multi-discipline study. Interdisciplinary research can bring more vitality and possibilities to the subject. Low band circuits try to use visual LED demonstration to show the results of group speed control. In the future, there is also a lot of research space by deep learning, continuous system simulation and other methods.

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