

## Cascade analysis on the ultrafast all-optical NOT gate based on high nonlinear Sagnac interferometer

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**Abstract:** All-optical logic gates are the basic unit of all-optical computer and all-optical network in the field of communication in the future. A variety of structures and methods has been proposed for the implementation of all-optical logic gate, however, the bottleneck of this technique has emerged, which is how to cascade the individual all-optical logic gates to achieve more complex logical relationships. The existing schemes for all-optical logic gate, generally, don't have excellent cascade to realize multilevel connection. And the existing analysis on the cascade usually stays on the theoretical level without combination with the realistic situation, which have little sense for the practical application. This work has presented a novel ultrafast all-optical NOT gate based on high nonlinear Sagnac interferometer, has built its mathematical model and digital model, has adopted Gauss pulse as input light for simulation, which is more realistic, and has analyzed the system cascade on the basis of simulation results. The analysis of cascade has taken into account the influence of fiber loss and walk-off effect. The basic conclusions in this article show that the proposed scheme of all-optical logic gates can maintain excellent cascade under practical situation with interference factors.

**Key words:** all-optical logic gate; HLNF; cascade

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## 基于高非线性 Sagnac 干涉仪的超高速全光 NOT 门可级联性研究

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**摘 要:** 在未来的通信领域中, 全光逻辑门是全光计算机和全光网络的基本单元。目前已经提出了很多实现全光逻辑门的结构和方法, 但是全光逻辑的技术瓶颈也出现了, 就是怎样能够将单个的全光逻辑门级联起来实现更复杂的逻辑关系。现存的全光逻辑门结构一般不具有很好的可以实现多级连接的级联性, 而且现有的对于级联性的分析大都停留在理论层面, 而没有与实际情况相结合, 所以对于实际应用来说意义很小。提出了一种新型的基于高非线性 Sagnac 干涉仪的超高速全光 NOT 门, 建立了它的数学模型, 采用了与实际情况更加接近的高斯脉冲模拟输入光, 并且在仿真结果的基础上分析了系统的级联性, 对级联性的分析考虑了光纤损耗和走离效应的影响。得到的基本结论表明, 所提出的全光逻辑门的结构能够在实际情况下保持良好的级联性。

**关键词:** 全光逻辑门; 高非线性光纤; 可级联性

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## 0 Introduction

In the field of information technology, the superior way to reach a high processing speed currently, is using multi-core super computer, whose processing speed can reach a trillion times. However, due to the limitation of principle and materials, processing speed that electronic computers can achieve is limited ultimately. This problem has prompted the development of all-optical communication, which is predicted to take the place of photoelectric communication in information technology in the future. Since light has excellent characteristics such as fast transmission speed and the ability of carrying a large amount of information, the all-optical communication technology can meet lots of requirements that electric-optical network cannot. All-optical logic gates, the subject this work focused on, are the basis and premise of the all-optical network and all-optical computer. Various principles, structures and devices have emerged out for realizing all-optical logic gates, such as semiconductor optical amplifier (SOA)<sup>[1-2]</sup>, quantum dot semiconductor amplifier (QD-SOA)<sup>[3-4]</sup>, optical parametric amplifier (OPA)<sup>[5]</sup>, semiconductor optical amplifier compound interferometer<sup>[6]</sup>, and nonlinear interferometer<sup>[7]</sup>, etc<sup>[8-10]</sup>. Although the single all-optical logic gates have been intensively studied, the fact that the existing schemes for all-optical logic gates mostly can't be cascaded feasibly and easily still exists, and the previous study on the cascade is only focus on the ideal situation, which isn't applicable to the practical use.

To solve the problem, this work proposed a novel structure of all-optical logic gates. The scheme adopted a new component called high nonlinear fiber (HNLF), which has a higher nonlinear coefficient, so that can improve the speed limit greatly. Moreover, this article uses Gauss pulse instead of square wave to simulate real light pulse, which is more reasonable and more close to the reality. This work also presented a detailed analysis of the cascade of the all-optical logic gates based on high nonlinear optical fiber Sagnac interferometer, considering

interference factors such as fiber loss and walks off effect, and proved that the scheme proposed by this article had good cascade in practical application.

## 1 Principle of operation

This work selected all-optical NOT gate based on high nonlinear Sagnac interferometer as the object of the study. The innovation of this work is that the high nonlinear fiber has been used as the medium of cross phase modulation (XPM) effect, and have selected femtosecond laser as a high power light source, together with the reasonable optical design, this novel structure can not only realize all-optical NOT logic function successfully, but also improve the cascade of the system.

As shown in Fig.1, the specific principle of the NOT logic is as follows. The pump light pulse is split into two beams by the Y coupler, transmitted along the clockwise (CW) and counterclockwise (CCW) direction respectively. The beam transmitted CW enters the HNLF together with the signal light, while the beam transmitted CCW directly entering the HNLF alone. When the signal light is bright light (represents logic "1"), it makes the CW beam experience the cross phase modulation effect, thus produce a phase shift and have a phase difference of  $\pi$  with the CCW beam. So the intensity of output light will be attenuated by the interference happened in Y coupler between the CW and CCW beam, which will cause the output light to be weak light (represents logic "0"). On the contrary, when the signal light is weak light (represents logic "0"), neither of the two beams can produce a phase shift, so there is no interference in the output coupler, which makes the output light still be bright light

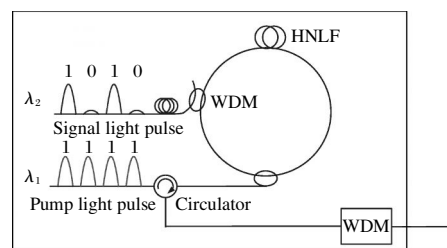


Fig.1 Optical structure of the "ultrafast all-optical NOT gate based on high nonlinear Sagnac interferometer" system

(represents logic "1"). In a word, the optical structure shown in the figure can realize the logic function of NOT feasibly.

## 2 Modeling

This section has established the mathematical model of the "ultrafast all-optical NOT gate based on high nonlinear Sagnac interferometer", and the discrete mathematical model for simulation has also been derived.

### 2.1 Theoretical model

According to the Maxwell equations that the optical pulses must satisfy when propagated in the fiber, the equation of the light intensity of each beam propagated in the fiber can be obtained.

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2} A = i\gamma |A|^2 A \quad (1)$$

where  $\alpha$  denotes the fiber loss coefficient,  $\gamma$  stands for the fiber nonlinear coefficient, obtained by:  $\gamma = n_2 \omega_0 / c A_{\text{eff}}$  (where  $A_{\text{eff}}$  is the effective cross section of the HNLF).  $\beta_1$  and  $\beta_2$  indicate dispersion of the fiber, depended on the refractive index, expressed as:

$$\beta_1 = \frac{n_g}{c} = \frac{1}{c} \left( n + \omega \frac{dn}{d\omega} \right), \beta_2 = \frac{1}{c} \left( 2 \frac{dn}{d\omega} + \omega \frac{d^2 n}{d\omega^2} \right) \quad (2)$$

where  $n_g$  is the group refractive index, and  $v_g$  is the group velocity of the propagating signal.

In the optical system of the all-optical NOT gate proposed in this work, when the pump light and the signal light pass through the HNLF simultaneously, they will influence each other's refractive index and create a phase shift, which is called cross phase modulation (XPM) effect. Compared with the condition before XPM effect, the light will gain a nonlinear phase shift, determined by the intensity of both lights, which is calculated as follows:

$$\phi_j^{\text{NL}}(z) = \frac{\omega_j z}{c} \Delta n_j = \frac{\omega_j z n_2}{c} (|E_j|^2 + 2|E_{3-j}|^2) \quad (3)$$

where  $j=1$  or  $2$ . The first term on the right side of the formula is produced by self phase modulation, and the second by cross phase modulation, whose value is obviously the two times of the first one, so plays the more important role in the phase determination process.

The combination of (1) and (3) will give us the

nonlinear coupled equations of the light intensity of each beam after experiencing cross phase modulation effect.

$$\frac{\partial A_{p1}}{\partial z} + \frac{1}{v_{gp1}} \frac{\partial A_{p1}}{\partial t} + \frac{i}{2} \beta_2(\lambda_p) \frac{\partial^2 A_{p1}}{\partial t^2} + \frac{\alpha_1}{2} A_{p1} = i\gamma_1 [|A_{p1}|^2 + 2|A_{s1}|^2] A_{p1} \quad (4)$$

$$\frac{\partial A_s}{\partial z} + \frac{1}{v_{gs}} \frac{\partial A_s}{\partial t} + \frac{i}{2} \beta_2(\lambda_s) \frac{\partial^2 A_s}{\partial t^2} + \frac{\alpha_2}{2} A_s = i\gamma_2 [|A_s|^2 + 2|A_{p1}|^2 + 2|A_{p2}|^2] A_s \quad (5)$$

$$\frac{\partial A_{p2}}{\partial z} + \frac{1}{v_{gp2}} \frac{\partial A_{p2}}{\partial t} + \frac{i}{2} \beta_2(\lambda_p) \frac{\partial^2 A_{p2}}{\partial t^2} + \frac{\alpha_1}{2} A_{p2} = i\gamma_1 [|A_{p2}|^2] A_{p2} \quad (6)$$

where formula (4) is the coupled equation for the CW pump light, (5) is the coupled equation for the CW signal light, and (6) is the coupled equation for the CCW pump light.

As the result of XPM, the pump light acquires a nonlinear phase shift against its other copy, which creates a relative phase difference between them:  $\Delta\phi = \phi_1 - \phi_2$ . When they once again return to the Y coupler to form one beam of output light, the power of output light after interference is determined by the intensity and phase difference of the two beams, the corresponding formulas read:

$$P_t = A_1^2 + A_2^2 + 2A_1 A_2 \cos(\phi_1 - \phi_2) \quad (7)$$

This formula indicates that the result of the all-optical logic gate is determined by the phase difference of two pump beams: when  $\phi_1 - \phi_2$  is  $\pi$ , the output power  $P_t$  is 0, the output light being weak light, on the other hand, when  $\phi_1 - \phi_2$  is 0, the output power  $P_t$  equals to the input power, the output light being bright light.

### 2.2 Simulation model

To establish the simulation model of the optical system of "ultrafast all-optical NOT gate based on high nonlinear Sagnac interferometer", it's essential how to obtain the solution of the nonlinear coupled equations (formula (4)–(6) in section 2.1). Since the coupled equations are nonlinear partial differential equations, which are difficult to obtain the analytical solutions, an iterative method is employed to get their numerical solutions, making substitute for the analytical solutions. In

general, that is to discrete the continuous domain and to replace differential with difference, which is an approximation method called the finite difference method.

The first step is to divide  $L$ , the length of the fiber, into  $m$  small parts, and similarly, divide  $T$ , the pulse duration, into  $k$  small parts, expressed as  $\Delta z=L/m$  and  $\Delta t=T/k$ . With ignoring the fiber loss, which is necessary to simplifying the calculation, difference is replaced by differential in the nonlinear coupled equations (4),(5),(6), and the iterative formulas of light intensity of each beam related to location and time can be written as follows:

$$A_{s_{n+1}}^i = A_{s_n}^i - \frac{\Delta z}{2\Delta z} \left( \frac{1}{v_{gs}} - \frac{1}{v_{gp}} \right) (A_{s_n}^{i+1} - A_{s_n}^{i-1}) - \frac{i}{2} \beta_2(\lambda_s) \Delta z \frac{A_{s_n}^{i+1} + A_{s_n}^{i-1} - 2A_{s_n}^i}{\partial t^2} + \Delta z i \gamma_2 \left[ |A_{s_n}^i|^2 + 2|A_{p1_n}^i|^2 + 2|A_{p2_n}^i|^2 \right] A_{s_n}^i \quad (8)$$

$$A_{p1_{n+1}}^i = A_{p1_n}^i - \frac{i}{2} \beta_2(\lambda_p) \Delta z \frac{A_{p1_n}^{i+1} + A_{p1_n}^{i-1} - 2A_{p1_n}^i}{\Delta t^2} + \Delta z i \gamma_1 \left[ |A_{p1_n}^i|^2 + 2|A_{s_n}^i|^2 \right] A_{p1_n}^i \quad (9)$$

$$A_{p2_{n+1}}^i = A_{p2_n}^i - \frac{i}{2} \beta_2(\lambda_p) \Delta z \frac{A_{p2_n}^{i+1} + A_{p2_n}^{i-1} - 2A_{p2_n}^i}{\Delta t^2} + \Delta z i \gamma_1 \left[ |A_{p2_n}^i|^2 + A_{p2_n}^i \right] \quad (10)$$

where formula (8) is the iterative equation for the CW pump light, (9) is the iterative equation for the CW signal light, and (10) is the iterative equation for the CCW pump light.

After the calculation above, the numerical model for the proposed all-optical NOT gate has been obtained, which is especially appropriate for simulation programming. On this basic model, this work chose Matlab as simulation environment, and then selected the proper initial value, the parameter value and the step size according to the characteristics of the input light and the fibers used.

### 3 Results and discussion

This section has presented the simulation result of the ultrafast all-optical NOT gate based on high nonlinear Sagnac interferometer, and further more, and the factors

including fiber loss and walk off effect, which all have a noticeable influence on the cascading of the all-optical logic gate, has been analyzed attentively.

The values of the simulation parameters are determined by characteristics of the lab materials and experimental equipments. The type of the HNLF adopted is NL-1550-Zero, whose effective cross section is  $A_{\text{eff}}=11 \mu\text{m}^2$ , the nonlinear refractive index is  $n_2=2.76 \times 10^{-20} \text{ m}^2/\text{W}$ , and the length used in this simulation is 140 m. Therefore, the nonlinear coefficient needed in the iterative equation (8)-(10) can be calculated by the formula  $\gamma=n_2\omega_0/cA_{\text{eff}}=2\pi n_2/\lambda A_{\text{eff}}$ , where the values of the wavelength are determined by the light source: wavelength of pump light  $\lambda_p=1.5494 \times 10^{-6} \text{ m}$ , wavelength of signal light  $\lambda_s=1.5468 \times 10^{-6} \text{ m}$ . In the iterative equation, the dispersion related coefficients  $\beta_1, \beta_2$  can be calculated according to the function relationship between medium refractive index and light frequency:

$$\beta_1 = \frac{1}{c} (n + \omega \frac{dn}{d\omega}), \beta_2 = \frac{1}{c} (2 \frac{dn}{d\omega} + \frac{d^2n}{d\omega^2}) \quad (11)$$

where  $n$  and  $\omega$  bear such connection:  $n^2(\omega) = 1 + \sum_{j=1}^m \frac{B_j \omega_j^2}{\omega_j^2 - \omega^2}$ ,

the constants depended on the medium are:  $m=3$ ,  $B_1=0.6961663$ ,  $B_2=0.4079426$ ,  $B_3=0.8974794$ ,  $\omega_1=2.7537727 \times 10^{16}$ ,  $\omega_2=1.6205061 \times 10^{16}$ ,  $\omega_3=1.9034643 \times 10^{14}$ . After figuring out values of  $\beta_1, \beta_2$ , group velocity can be obtained by its relationship with  $\beta_1: v_g=1/\beta_1$ . Gauss pulse has been adopted to simulate real optical pulse, which is considered more reliable in the field of optical communication, since real optical pulse always has the waveform approximated to Gaussian distribution. This work has assigned the initial power of both pump light and signal light to 1 000 W. Considering the complexity of the iterative procedure, and the stability of the algorithm, the step size is set as  $\Delta z=0.5 \text{ m}$ ,  $\Delta t=0.1 \text{ ps}$ , so that the program can ensure the precision of calculation and the reasonable amount of computation at the same time.

As shown in Fig.2 above, Fig.2(a) is the input signal light pulse "0101010", Fig.2 (b) is the input pump light pulse which is always bright light, Fig.2 (c) gives the waveform of phase difference between two beams of

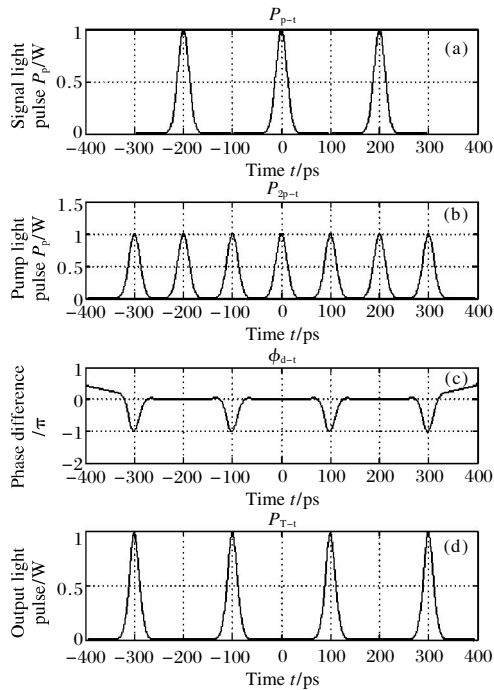


Fig.2 Simulation results of the 'ultrafast all-optical NOT gate based on high nonlinear Sagnac interferometer' system

pump light, and Fig.2 (d) indicates the output light pulse '1010101'. The results of simulation verify that the intensity of output light sequence is related to the phase difference, and is just the opposite of the input signal sequence through XPM effect and interference effect, which satisfies the logical relationship of NOT and conforms to the mathematical model.

Since the optical scheme of the "ultrafast all-optical NOT gate based on high nonlinear Sagnac interferometer" selected is encoded according to the light intensity, as bright light for logic "1" and weak light for logic "0", consequently, whether intensity of the output light is strong enough to express the logic state accurately and can serve as the input light of next level, plays the most important role in deciding whether the scheme has a great cascade. So in this section, the intensity of the output light is selected as the judging criterion of cascade of the system.

The simulation results represent the output intensity in ideal situation, which means the influence factors such as fiber loss are ignored during the process, so that the output intensity isn't be attenuated seriously. But in

reality, with objective factors such as fiber loss, walk-off effect, always existing, the light will have a certain degree of attenuation when passing through each level of logic gates. Considering the fiber loss and the walk away effect, this work analyzed the influence they had on the cascade of the system, based on the ideal case of simulation.

### 3.1 Fiber loss

The fiber loss causes the attenuation of input intensity, and obviously, the intensity of input pump light and signal light would have an impact on the output power. The function of the two factors is analyzed respectively, using power instead of intensity to represent input light, in order to facilitate the expression.

Fig.3 shows the curve of the output power varied with the attenuation of power of the input signal light. An attenuation coefficient  $\alpha_s$  is set to represent the power variation of the signal light, while keeping the pump light power and the other parameters constant. With the attenuation coefficient varied from 1 to 0, which indicates the process of signal light decreases from the initial power 1 000 W to 0 W, the output power, which should be 0 originally, is gradually increasing and the slope of the curve is also increasing. In addition, when the power of the signal light decreases slightly, the slope of the variation of output power is very small, even close to zero, which means it has little effect on the output power and also the expression of the output logic state, so the system still maintain a good cascade.

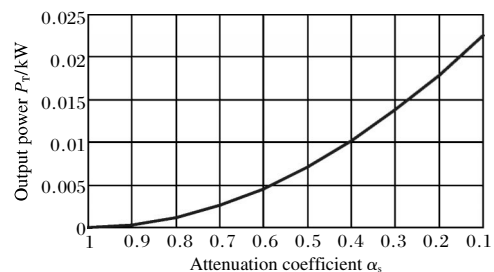


Fig.3 Variation of output power with the attenuation of the signal light

Fig.4 shows the curve of the output power varied with the attenuation of power of the input pump light. Another attenuation coefficient  $\alpha_p$  is set to represent the power variation of the pump light, while keeping the

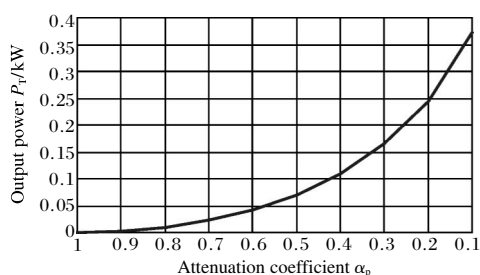


Fig.4 Variation of output power with the attenuation of the pump light

signal light power and the other parameters constant. With the attenuation coefficient varied from 1 to 0, which indicates the process of pump light decreases from the initial power 1 000 W to 0 W, the output power, which should be 0 originally, is gradually increasing and the slope of the curve is also increasing. Similarly, as the power of the pump light decreases slightly, the slope of the variation of output power is also close to zero. The more the input pump light been attenuated, the more influence it will make on the output power. However, in an all-optical logic gate system, generally, the output light will always be used as the signal light of the next level, but not the pump light, so the pump light does not need to cascade, which means the attenuation of the pump light has little effect on the cascade of the whole system.

### 3.2 Walk off effect

When two pulses of light with different wavelengths  $\lambda_1, \lambda_2$  propagate in the same waveguide, due to the difference of the group velocity  $v_{g1}, v_{g2}$  the original synchronous pulses will no longer overlap with pulse center deviated, which is called the "walk off effect" caused by the group velocity mismatch (GVM). The walking-off distance, which is the desired distance of two pulses of light start to deviate, can be calculated by the formula  $L_{w0} = \tau_0 / \left| \frac{1}{v_{g1}} - \frac{1}{v_{g2}} \right|$ , where  $\tau_0$  is the pulse width. This formula indicates that the bigger the wavelength difference between the signal light and the pump light is, the bigger their group velocity difference will be, the shorter the walking-off distance they need, and the more serious the walk off effect will be, which could make the XPM effect not sufficient enough to produce the precise

phase difference  $\pi$ , and greatly influence the output power.

As shown in Fig. 5, the output waveforms for three different signal wavelengths are also different in both output power and output pulse center. The pump wavelength and other parameters are kept constant, and three different values are selected to assign the signal wavelength, which are  $\lambda_s = 1.5482 \mu\text{m}$  expressed by solid line,  $\lambda_s = 1.5468 \mu\text{m}$  expressed by dotted line, and  $\lambda_s = 1.5510 \mu\text{m}$  expressed by dash line, respectively. This result of simulation shows that if the wavelength of signal light is closer to the pump light, the output light will have better optical properties, such as higher output power and minor deviations caused by walk off effect. Moreover, when the wavelength difference between the the signal light and the pump light reaches the nm level, variation of the output power caused by walk off effect is only 0.01 kW order of magnitude, and the offset of the output pulse center is only ps order of magnitude, which is not enough to confuse the expression of the output logic state.

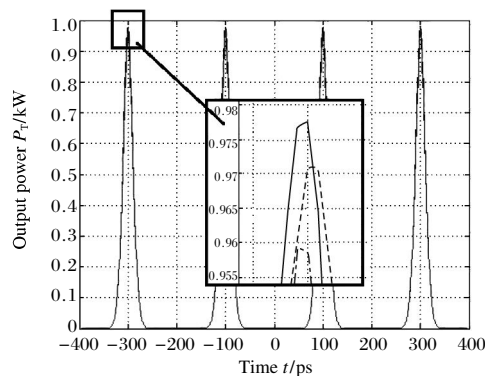


Fig.5 Three difference waveforms with three difference wavelengths of the signal light

## 4 Conclusion

In conclusion, the scheme of "ultrafast all-optical NOT gate based on high nonlinear Sagnac interferometer" has been presented, the mathematic model has been built, and the simulation model has also been derived with the finite difference method. The results of the simulation highly conformed to the expected results. Based on this result, the cascade of the system has been discussed,

setting the output power as the criterion.

Based on the results of the ideal simulation model, this paper has analyzed the cascade of this all-optical logic gate in the presence of interference conditions of fiber loss and walk off effect. Conclusions show that the "ultrafast all-optical NOT gate based on high nonlinear Sagnac interferometer" proposed in this work can keep excellent cascade with these actual factors taken into account. As the power of the input signal light and pump light attenuated slightly by fiber loss, which is an usual phenomenal in reality, the output power changed only in small amplitude, which, had little effect on the cascade of the system. Under the influence of walk off effect caused by wavelength difference between signal light and pump light, the difference of nm level only produce very small variation of output power, and slight offset of output pulse center. The results above indicates that the structure of all-optical logic gate proposed in this work have certain tolerance to actual interference factors such as fiber loss and walk off effect. The scheme can maintain good cascade and is suitable for the cascade of all-optical logic gate system.

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