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Highly efficient single-pixel imaging system based on the STEAM structure

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Abstract: We propose and demonstrate a compact and highly efficient single-pixel imaging system with data compression based on the traditional serial time-encoded amplified microscopy (STEAM) structure. Our proposal solves the big data issue and low-efficiency bottleneck in the conventional STEAM systems. Also, a cascaded Mach-Zehnder interferometric (MZI) structure as the optical random pattern generator is proposed and experimentally demonstrated as the low-cost approach to achieve data compression. A 45° tilted fiber grating (TFG) is applied to increase the efficiency of the imaging system. A state-of-art experiment is performed and data compression ratios from 5% to 20% at an imaging size of 1mm*1.8mm are conducted using our proposed system for the first time to the best of our knowledge. The proposed optical imaging system mitigates the big data issue, decreases the system cost, and increases energy efficiency, and lays a solid foundation for low-cost, compact, and highly efficient ultrafast optical imaging.

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1. Introduction

Single-pixel imaging systems, which employed single-pixel detectors instead of expensive cameras, have the benefits of low-cost in some wavebands and ultrafast imaging speed up to tens of megahertz even gigahertz [1,2]. Hence, single-pixel imaging followed by compressive sensing (CS) [3–8] was studied and reported by a variety of worldwide researchers. The single-pixel imaging systems are mainly achieved via the employment of structured illumination [9], structured detection [10], modulation schemes [11], and sampling schemes [12].

Serial time-encoded amplified microscopy (STEAM) [13] is one type of single-pixel imaging system, which enables unprecedented ultrafast imaging speed with a record of 4.4 trillion frames per second [14]. STEAM contains two main parts: one is one-to-one mapping between the wavelength and time using dispersive devices, such as dispersive compensating fiber (DCF) [15]; another one is one-to-one mapping between wavelength and space using spatial dispersive devices, such as diffraction grating [16]. STEAM has been successfully utilized in flowing particle screening [17], ultrafast optical imaging [18–20], light ranging [21], and compressive sensing imaging [4,22,23]. However, the traditional STEAM has two drawbacks: one is the big

data issue resulting from the high throughput, and the other is the low-efficiency issue induced by the diffractive devices.

The conventional solution to the big data issue in the STEAM system is using CS. The utilization of CS can greatly reduce the detected data volume and the detection cost of imaging system using low-bandwidth and low-cost photodetectors (PDs) and analog-to-digital converters (ADCs) [24–26]. To perform the CS method in imaging systems, pseudorandom binary sequences (PRBS) as the random patterns are required. The PRBSs are normally generated by arbitrary waveform generators (AWGs), which could obtain an ultrafast speed up to 10 GHz or even more [24]. However, this approach requires expensive devices. An alternative low-cost approach is generating the PRBSs in the spatial domain using spatial light modulator [11] or coated fiber tip [26]. However, this method has limited imaging speed (up to 300 KHz). To handle this trade-off between the two approaches, a single-mode fiber (SMF-28)-based cascaded Mach-Zehnder Interferometric (MZIs) structure as the low-cost optical random pattern generator with the benefit of exterminating the expensive AWGs is proposed. The cascaded MZIs structure involves a fiber-based dual-MZI structure.

The diffractive devices induced low-efficiency problem is mitigated by the employment of 45° tilted fiber grating (TFG). The 45° TFG in our previous report [27] is a compact and highly efficient in-fiber diffraction device, which could greatly reduce the volume and increase the efficiency of the imaging system. The core device volume from bulky grating to in-fiber grating is reduced by 99%. The energy efficiency is improved from 75% to 93% thanks to the employment of the 45° TFG. Also, the 45° TFG has the feature of strongly polarization-sensitive due to the destroyed of symmetrical structure. The 45° TFG performs as the light emitter, in-line polarizer, and side diffraction device, simultaneously in the proposed imaging system. Recently, the 45° TFG has been implemented in ultrafast imaging [18], remotely optical sensing [28] and free-space optical communication [29,30].

In this work, we propose a highly efficient single-pixel imaging system with data compression. To perform data compression, the fiber based two-MZI structure is used to generate the PRBSs that required in the CS method. And the 45° TFG is utilized to reduce the volume and increase the efficiency of the imaging system. The experimental results show data compression ratios from 5% to 20% are obtained and the reconstruction of two lines matched quite well. Our proposal holds great potential for low-cost, compact, and highly efficient imaging systems.

2. Experimental section

The structure of the SMF-based 45° TFG is described in Fig. 1, which shows the S-polarized light for wavelength-dependent side diffraction and P-polarized light for direct transmission. Also, due to the intrinsic feature of componential attenuation, the light intensity emitted out of the 45° TFG is attenuated along the transmission axis of the fiber. The detailed introduction of the 45° TFG can be found in the previous publication [31]. A 45° TFG is inscribed in the core of SMF-28 using a UV light with a center wavelength of 244 nm and a standard phase mask. A 33.3° rotation of the phase mask is performed to achieve the 45° tilted angle [32]. The 45° TFG employed in our experiment has a length of 24 mm and a grating period of 748 nm. The division of changes in angles and changes in wavelengths is defined as the angular dispersion D , which is expressed as

$$D = \frac{d\theta(\lambda)}{d\lambda} = -\frac{n\sin(2\theta)}{\lambda} = -\frac{n}{\lambda} (\theta = 45^\circ) \quad (1)$$

where θ is the tilted angle of TFG, n is the refractive index of the fiber core, λ is the wavelength of the incident light. The Eq. (1) illustrates that the 45° TFG has the maximum angular dispersion.

The diagram of the proposed single-pixel imaging system is depicted in Fig. 2. A broadband pulsed mode-locked laser (MLL) is utilized as the light source, which has a repetition rate of 50 MHz and a stable output optical power of 7 dBm. A DCF with a total dispersion of -0.64

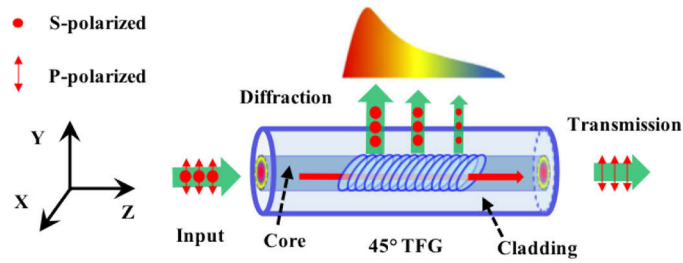


Fig. 1. Schematic of the 45° TFG. TFG: tilted fiber grating

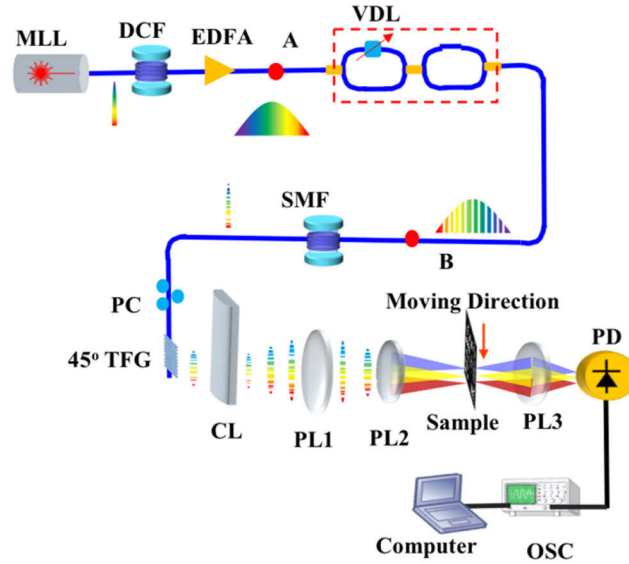


Fig. 2. Schematic of the proposed single-pixel imaging system with data compression. MLL: mode-locked laser; DCF: dispersive compensating fiber; EDFA: Erbium doped fiber amplifiers; VDL: variable delay line; SMF: single-mode fiber; PC: polarization controller; CL: cylindrical lens; PL: plano-convex lens; PD: photodetector; OSC: oscilloscope.

ns/nm is applied to achieve the one-to-one mapping between the wavelength and time. The femtosecond ultrafast short optical pulses propagate through the DCF and the short pulses are stretched in time domain from femtosecond to nanosecond. Then, the stretched pulses go through the Erbium doped fiber amplifier (EDFA), where the pulses are amplified to obtain higher signal-to-noise ratio (SNR). The details of MZIs structure is shown inside of the red dotted box. The stretched and amplified pulses pass through the cascaded MZIs structure, where the pulses are modulated by changing the optical path differences (OPDs) in the variable delay line (VDL) device. In our experiment, the OPDs are changed from 1mm to 100mm with a step of 1mm using a manually VDL device. Hence, the random patterns are generated by the cascaded MZIs structure. Figure 3(a) and 3(b) show the pulse in spectrum domain and temporal domain before the cascaded MZIs structure at point “A”, which indicate a full width at half maximum (FWHM) spectrum of 15nm from 1547nm to 1562nm in spectrum domain and a FWHM pulse duration of 9.6ns in temporal domain. Figure 3(c) and 3(d) show the pulse in spectrum domain and temporal domain after passes through the cascaded MZIs structure at point “B”. The free spectral ranges (FSRs) can be easily observed whether in spectrum domain or temporal domain.

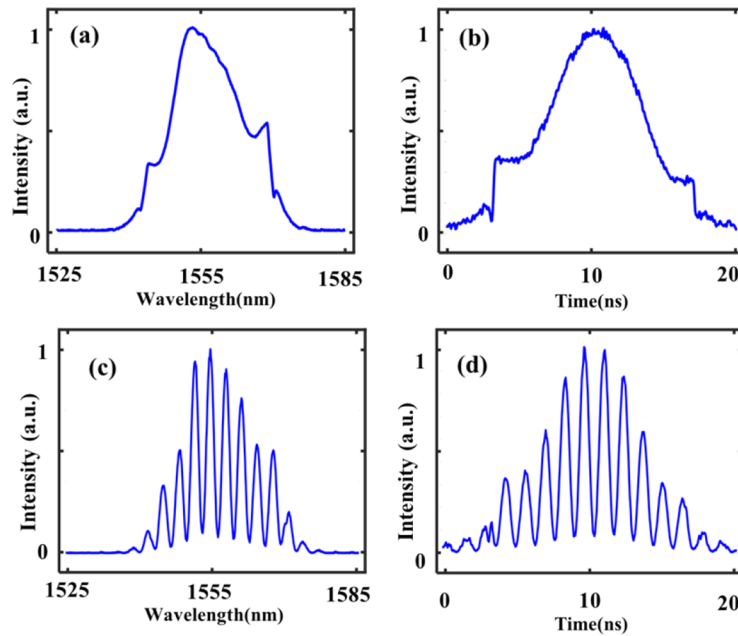


Fig. 3. Output wavelength of the MLL pulse before (a) and after (c) the cascaded MZIs structure in spectrum domain; Output waveform of the MLL pulse before (b) and after (d) the cascaded MZIs structure in temporal domain.

The quality of the random patterns generated by the cascaded MZIs structure is examined. OPDs from 1mm to 100mm with a step of 1mm are applied to the cascaded MZIs structure. Three continuous random optical patterns in temporal domain are illustrated in Fig. 4(a). And the results of pattern correlation coefficient of 100 continuous optical pulses is shown in Fig. 4(b), which confirms that the patterns have low correlation coefficient (an average value of 0.31) and are ideal candidates for CS imaging. Note in our experiment, the patterns are already reserved in the computer for future data processing.

The modulated pulses propagate through the cascaded MZIs structure and reach the 40km single-mode fiber (SMF-28, with a total dispersion of 0.64 ns/nm), where the stretched pulses are compressed into femtosecond pulses again. The compressed pulses go through the polarization controller (PC) and emit into free-space via the 45° TFG. Here, the 45° TFG performs as the incident light emitter, in-fiber lateral diffraction device and in-fiber polarizer. A cylindrical lens with a focal length of 20mm is put after the 45° TFG at a distance of 20mm for vertical light collimation. The collimated beam then passes through the lens set (two plano-convex lenses with focusing length of 150mm and 50mm and separated with a distance of 100mm), which is utilized to shrink and focus the beam onto the imaging plane. A 1951 USAF resolution target acting as the sample is vertically placed in our imaging system. After one line scanning, the sample is manually tuned to another vertical position. A plano-convex lens with a focusing length of 50mm is put after the sample for beam focusing. A single-pixel free-space PD with a bandwidth of 5GHz and an active area of 9499 μm^2 is employed to receive the collected light. The received data by the PD is shown in Fig. 5, which shows the intensities of the compressed pulses at every 20ns. Note in this experiment, a single-pixel PD with a bandwidth higher than 50MHz is enough, the reason here is we only have the 5GHz free-space PD. The received PD intensity information and the known random patterns are implemented to reconstruct the line scanning sample imaging. By multiple line scanning of the sample at varied vertical positions, a 2D imaging is recovered.

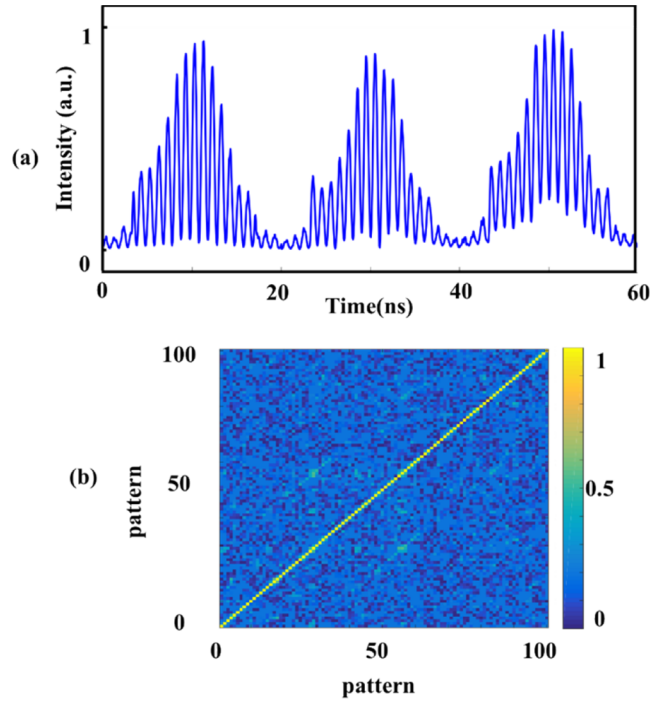


Fig. 4. (a) Three continuous waveforms in temporal domain; (b) Results of pattern correlation coefficient of 100 continuous optical pulses.

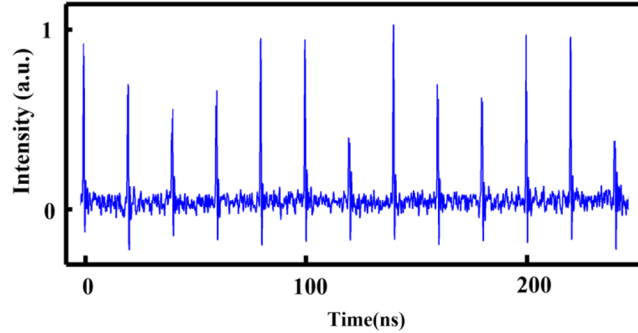


Fig. 5. Received data by the PD.

In our experiment, the imaging speed is determined by the time of patterns generation. For example, using ODL 100 (Thorlabs) as the VDL device. The VDL device tuning time is 500mm/s, for a 5% data compression, it needs to change 5mm OPD with a step of 1mm, and the time is 0.01s, hence the imaging speed is 100 fps. Regardless of the pattern generation and considering the beam scanning for a 2D imaging, a galvometer (QS7X-AG from Thorlabs, with a scanning speed up to 4KHz) is required. The MLL is employed for a ultrafast wavelength scanning in x-axis with a speed of 50MHz, and the galvometer is utilized for a slow y-axis scanning with a speed of 4KHz. With the current setup, the maximum imaging speed of our proposal is 100 fps. Note in our experiment, fast speed VDL device and fast speed galvometer can be employed to improve the imaging speed of the proposed imaging system.

In our experiment, the CS algorithm is based on the minimum l_1 norm reconstruction [33,34]. The scanning 1D line at a certain position of the sample ($I_{M \times 1}$) has a length of M points. The 1D line is mixed with the N times of random patterns, which are generated by the cascaded MZI structure. Each random pattern ($R_{M \times 1}$) has a length of M points. N is far smaller than M and equals the times of measurements. With N times of measurements, the measurement matrix can be illustrated as $R_{N \times M}$, which has a dimension of $N \times M$. $y_{N \times 1}$ is defined as the measurement vector, which is

$$y_{N \times 1} = R_{N \times M} \times I_{M \times 1} \quad (2)$$

To reconstruct the 1D line information, a convex optimization process is required, which is the process from $y_{N \times 1}$ to $I_{M \times 1}$. In our experiment, the measurement matrix $R_{N \times M}$ is the output from cascaded MZI structure, which is already reserved and known. The measurement vector $y_{N \times 1}$ is the received light intensity from the free-space PD. Hence, with the application of total variation (TV) minimization algorithm in our CS implementation [35,36], the 1D line imaging result is reconstructed. By reiteration of the 1D line reconstruct process, a 2D image consisting of multiple 1D lines is reconstructed.

In our experiment, the 1D line has a length of 100 points ($M=100$). The times of measurements (N) are 20, 15, 10, and 5, respectively. Figure 6(a) shows the 1951 USAF resolution target sample and the imaging area in the red rectangle with a field of view (FOV) of $1\text{mm} \times 1.8\text{mm}$. The imaging area is group 2, number 1 and the reconstructed image has a pixel size of 50×100 . The reconstructed imaging results at group 2, number 1 are described in Fig. 6(b)–6(e), which depict data compression ratios of 20%, 15%, 10%, and 5%, respectively. In our demonstration, the minimum times of measurement are 5 and the minimum data compression ratio is 5%, which is

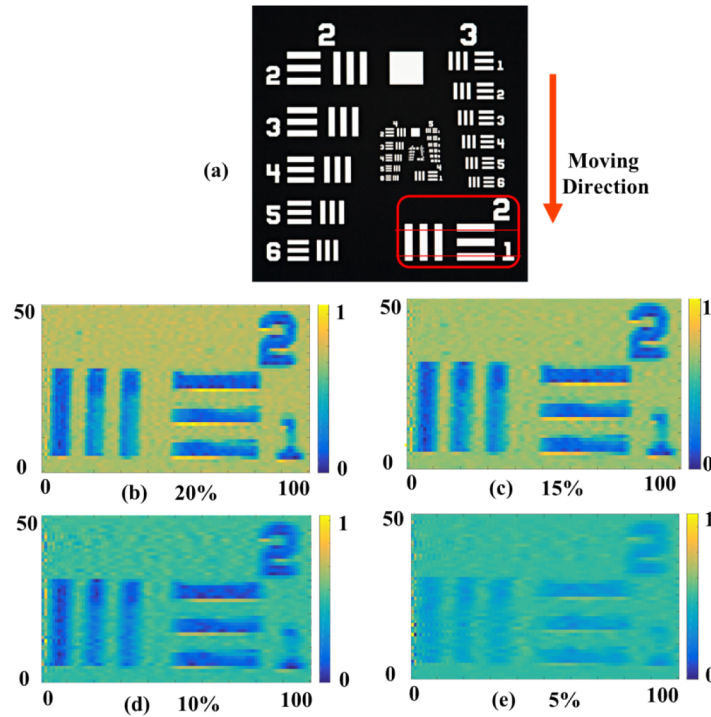


Fig. 6. (a) The 1951 USAF resolution target sample with red rectangular imaging area and two red scanning lines. The experimental results of reconstructed images with data compression ratios of (b) 20%, (c) 15%, (d) 10%, and (e) 5% respectively.

sample-rated. Take 5 times of measurement for an example, the imaging speed of this approach is 10 MHz considering the utilization of 50MHz MLL. When regarding the tuning time of VDL (such as DL100 in Thorlabs, 500mm/s) in the proposed imaging system, 5 times of measurement mean the 5 steps with each step of 1mm, the imaging speed is 10ms in time domain and 100Hz in frequency domain. The recovered images of different data compression ratios matched the original image in Fig. 6(a), which proves our proposal. To provide more detailed evidence, reconstructed line 6 and line 28 with varied data compression ratios in yellow, pink, green, and blue lines are showed in Fig. 7(a) and 7(b), respectively. The scanning position of line 6 and line 28 are shown in the Fig. 6(a) (two horizontal red lines in the red box). The red lines in Fig. 7(a) and 7(b) are the ideal results in comparison with the yellow, pink, green, and blue lines (experimental results with data compression ratios of 20%, 15%, 10%, and 5%, respectively). From Fig. 7, it's easy to conclude that the reconstructed lines of varied data compression ratios suit the ideal results.

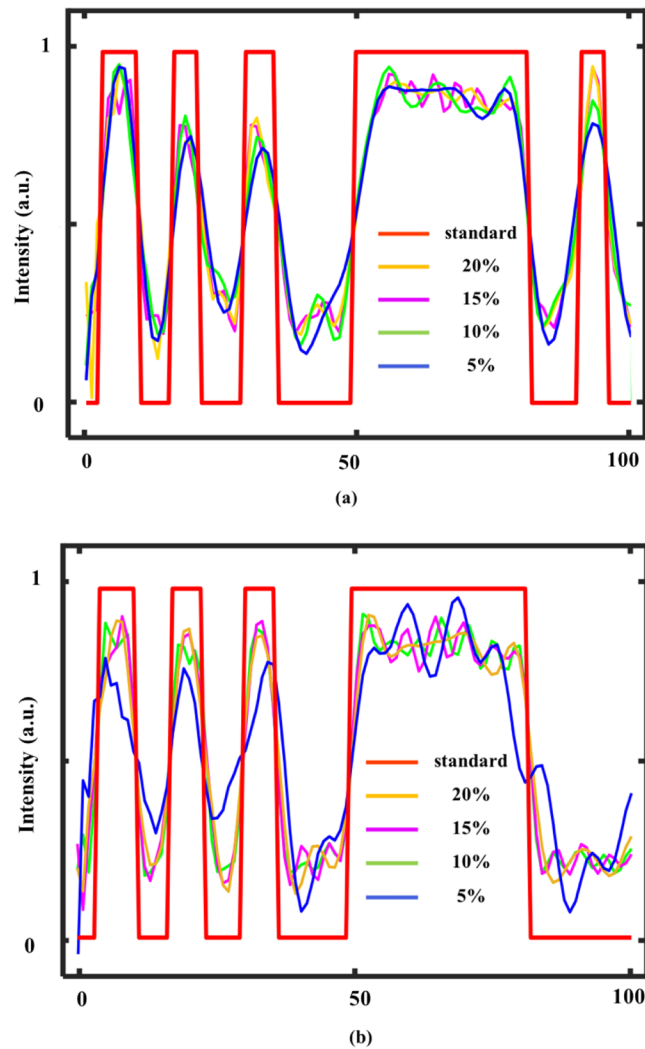


Fig. 7. The reconstructed experimental results (yellow, pink, green, and blue lines with data compression ratios of 20%, 15%, 10%, and 5%) and ideal results (red lines) of reconstructed (a) line 6 and (b) line 28, respectively.

3. Conclusion

In this work, we proposed and experimentally demonstrated a compact and highly efficient single-pixel imaging system based on STEAM structure with the benefits of data compression and low-cost detection. The big data issue is greatly mitigated in the traditional ultrafast single-pixel imaging system. A 45° TFG, which is acted as the light emitter, in-fiber diffraction device and in-fiber polarizer, is applied in our proposal to solve low-efficiency bottleneck. The application 45° TFG reduces the core device volume by 99% and improves the energy efficiency of the proposed imaging system from 75% to 93%. Besides, a low-cost SMF-based cascaded MZIs structure is demonstrated as a random pattern generator to implement the CS. The application of the cascaded MZIs structure could greatly reduce the detection cost of the proposed imaging system. The experimental results illustrate that a minimum data compression ratio of 5% is achieved with a FOV of 1mm×1.8mm and a pixel size of 50×100. The proposed imaging system achieves a continuous imaging speed of 100 fps, which could be easily improved by using a high-speed VDL device and a high-speed galvanometer. Our novel approach has great potential for ultrafast single-pixel imaging system with the advantage of low-cost, compact, and highly efficient required.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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