Biological micro resonators for whispering gallery mode lasing via droplet drying techniques

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Abstract. *In this study, we report the manufacturing and performance evaluation of biolasers based on the Whispering Gallery Mode (WGM) resonance effect, employing a solution composed of the natural protein bovine serum albumin (BSA) and the fluorescent dye Rhodamine B (RhB). We were able to create micro-resonators, including microspheres and quasi-spheres with well-defined shapes, by utilizing the micro-grating structures naturally on the surface of commercial compact discs (CDs) and adding a thin layer of edible oil. Experimental results demonstrate that both microsphere and quasi-sphere cavities can emit laser light with clear emission spectra, characterized by low lasing thresholds of approximately 1 µJ/pulse and high-quality factors (Q-factors) reaching up to 2883, when an optical pulsed Nd:YAG laser at a wavelength of 532 nm is used to excite the cavities. The considerable flexibility and elasticity of the BSA substrate enable tuning of the emitted wavelength by adjusting the shape of the resonance cavity. These findings highlight the potential of using biocompatible, low-cost, and readily available natural materials in the development of integrated micro-optical devices for biomedical applications.*

1. Introduction

Since their invention, lasers, recognized as one of the most significant discoveries of the twentieth century, have proven indispensable in various fields, including manufacturing, optical communication, medicine, and engineering [1]. Beyond traditional Fabry–Perot resonators, which offer high directionality, narrow linewidth, and high power, miniaturized microlasers have garnered increasing interest due to their advantages in integration with micro-optoelectronic and biomedical systems [2, 3]. In particular, biological microlasers have emerged as a promising class of devices because they utilize biocompatible and biodegradable materials, enabling direct operation in biological environments for applications such as biosensing [4], intracellular tracking [5], and implantable optical systems [6–8].

A variety of resonator geometries have been investigated for microlasers, including random laser cavities [9–11], distributed feedback structures [12], Fabry–Perot resonators [13], and whispering-gallery mode (WGM) cavities [14]. Among these, WGM-based biological microlasers are particularly attractive due to their compact size, high optical quality factors, and straightforward fabrication routes [15, 16]. For a WGM microlaser, three requirements must be satisfied: (1) a gain medium, (2) an excitation source, and (3) an optical feedback structure capable of confining light by total internal reflection along a smooth and symmetric boundary. Bovine Serum Albumin (BSA) has often been chosen as the host matrix because it is non-toxic, stable, and capable of forming solid structures, while Rhodamine B (RhB) provides a well-matched fluorescent gain medium [17–19]. Although dye-doped BSA microlasers have been extensively studied, the novelty of the present work lies not in the material system but in the fabrication method.

Conventional fabrication of dye-doped microlasers commonly relies on heating dye-containing solutions within polydimethylsiloxane (PDMS) matrices using a hot plate [15, 16]. In contrast, our work introduces a simple and cost-effective method for fabricating BSA/RhB microlasers by implementing the water-to-oil emulsion effect, thereby eliminating the need for PDMS or any thermal processing. When droplets of the protein–dye solution are deposited onto a thin oil layer, the interplay between the water-to-oil emulsion effect and gravitational forces promotes the formation of microcavities with spherical or quasi-spherical geometries, depending on the droplet size and the thinness of the oil layer. The formation of well-defined microcavities requires a uniform and continuous oil layer. However, achieving a homogeneous oil layer spreading on conventional substrates such as glass or silicon is challenging due to their hydrophilic surfaces and the intrinsic hydrophobic nature of oil.

To address these issues, in this work, we utilized an easily accessible commercial compact disc (CD) substrate, which facilitates the uniform coating of cooking oil and enables the formation of a thin, homogeneous layer. Without any heating, microresonators with different morphologies, including spheres and quasi-spheres, were spontaneously formed through natural drying. The microspheres exhibited clear lasing behavior, characterized by sharp spectral modes, a low lasing threshold of 1 μJ/pulse, and a cavity quality factor (Q-factor) of up to 2883. While the micro quasi-sphere demonstrated a higher threshold of 3 μJ/pulse. These results verify the feasibility of fabricating bio-friendly microlayers through an extremely simple and cost-effective method, highlighting their potential for integration into biosensing devices, intracellular tracking systems, and future non-invasive diagnostic platforms.

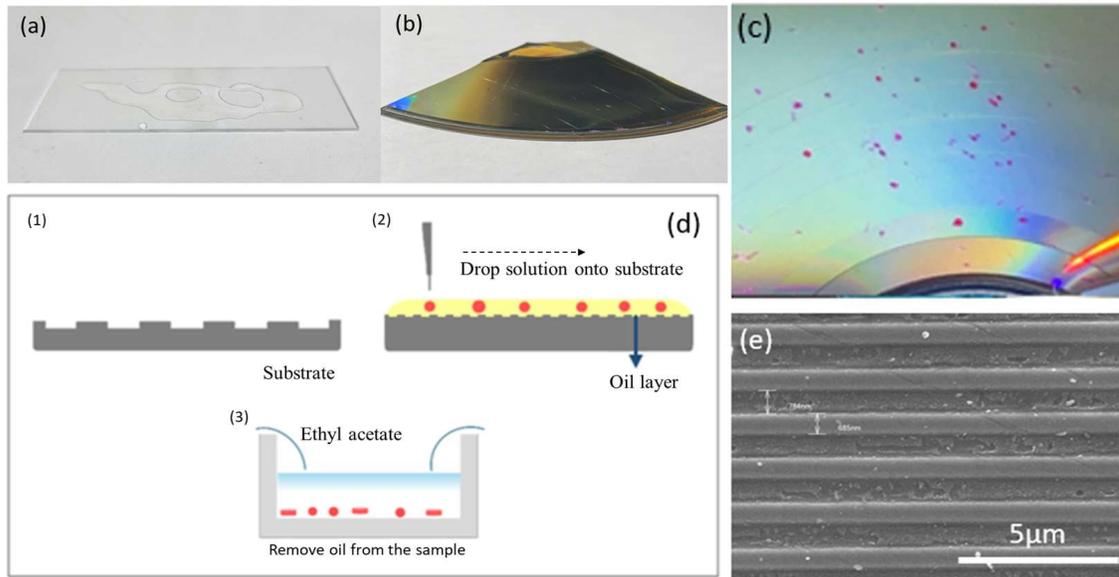## 2. Experiment

2.1. Fabrication method

Fig. 1. (a) Oil drops on a slide glass's surface; (b) A thin oil layer spreading on a compact disc (CD) surface; (c) Micro resonators fabricated on a CD disc; (d) Scheme of the micro resonator fabrication process on a CD coated with cooking oil; (e) SEM images of the CD after removing the protective label.

To evaluate the effect of substrate properties on microsphere formation, we compared the behavior of oil on a conventional glass slide (Fig. 1a) and on a compact disc (CD) surface (Fig. 1b). With the glass slide, it was not possible to achieve a thin and evenly spread oil layer, which limited control over droplet formation. In contrast, the inherent micro-groove patterns on CDs (Fig. 1e) act as natural alignment guides, enabling the oil to spread more thinly and uniformly than on a glass surface. This even distribution and adjustable thickness provide a more controlled environment for droplet formation, allowing the fabrication of both spherical and quasi-spherical microresonators. Therefore, CDs coated with an oil layer were selected as the hydrophobic substrate, offering a low-cost, readily available, and effective platform for micro laser fabrication.

Afterward, BSA/RhB droplets were then dispensed onto the oily surface using a fine needle, forming spherical or quasi-spherical droplets (Figs. 1c, 1d). These droplets were allowed to dry naturally under low-humidity conditions (<20%) for 24 hours (Fig. 1d-2) and were subsequently cleaned with ethyl acetate to remove excess residue (Fig. 1d-3).

The final morphology of the dried droplets—whether microspheres or micro quasi-spheres—was primarily determined by the oil layer thickness on the substrate. A thinner oil layer limited droplet contraction during solvent evaporation and, under the influence of gravity, caused the droplets to flatten slightly against the surface, forming quasi-spherical structures. In contrast, a thicker oil layer allowed more isotropic shrinkage dominated by surface tension, resulting in

well-preserved spherical shapes. By adjusting the oil layer thickness and taking into account gravitational effects, the droplet morphology can be controlled to transition between quasi-spherical and spherical forms.

2.2. Optical characterization

Optical images and surface morphologies of the microspheres and micro quasi-spheres formed from the BSA/RhB composite solution were captured using an optical microscope and a scanning electron microscope (SEM, FE-SEM NANOSEM450). The SEM system offers a resolution of up to 100,000X and allows for imaging at significantly higher depth of field, providing high-resolution surface details.

Properties of the microcavities were characterized using a micro-photoluminescence (μ-PL) system, which includes a 532 nm Q-switched nanosecond pulsed laser; a system of mirrors and lenses for directing and focusing the excitation beam onto the sample mounted on the microscope stage; a microscope equipped with 4X and 10X objective lenses and a 10X eyepiece; a spectrometer with a resolution of 0.2 nm connected to the microscope via an optical fiber; and a camera for capturing optical images through the microscope. The excitation beam was focused to a circular spot with a diameter of approximately 350 μm on the sample surface. Based on this spot size, the laser fluence (energy density) can be estimated using the formula $F = E/\pi r^2$. For example, at a pulse energy of 1.17 μJ, the fluence is about 12.2 mJ/cm^2, while at 19.7 μJ per pulse, it reaches approximately 205 mJ/cm^2. These values provide a quantitative measure of the excitation conditions used in the lasing experiments.
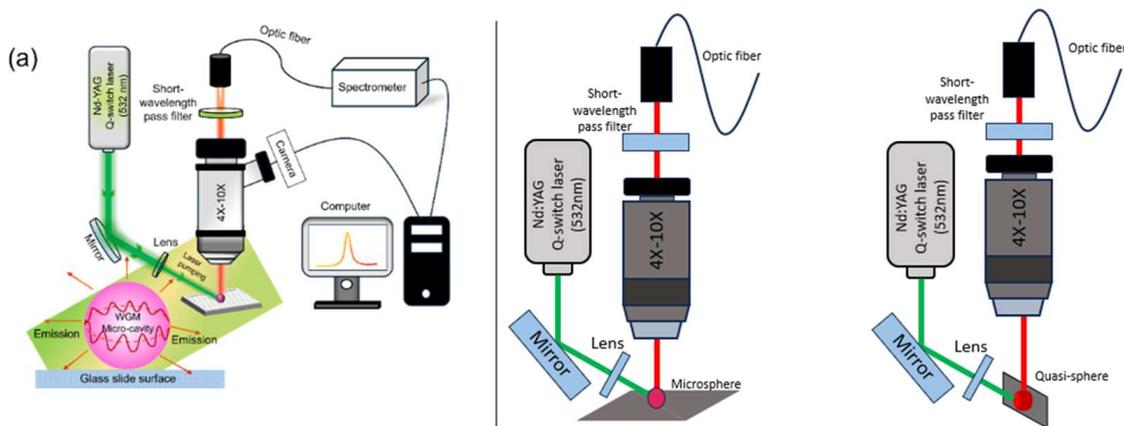

Fig. 2. (a) Schematic of the optical setup for WGM micro lasers measurement; (b), (c) Schematic of the optical setup for microsphere and quasi-sphere.

For the experimental setup, the microspheres emit laser light in all directions. In our case, they were pumped at an oblique angle, and the emission was collected vertically by the spectrometer fiber. For the micro quasi-spheres, the samples were rotated so that their horizontal plane was aligned with both the pump laser and the detection fiber, enabling efficient excitation and collection (Figs. 2b and 2c).

3. Results and discussion
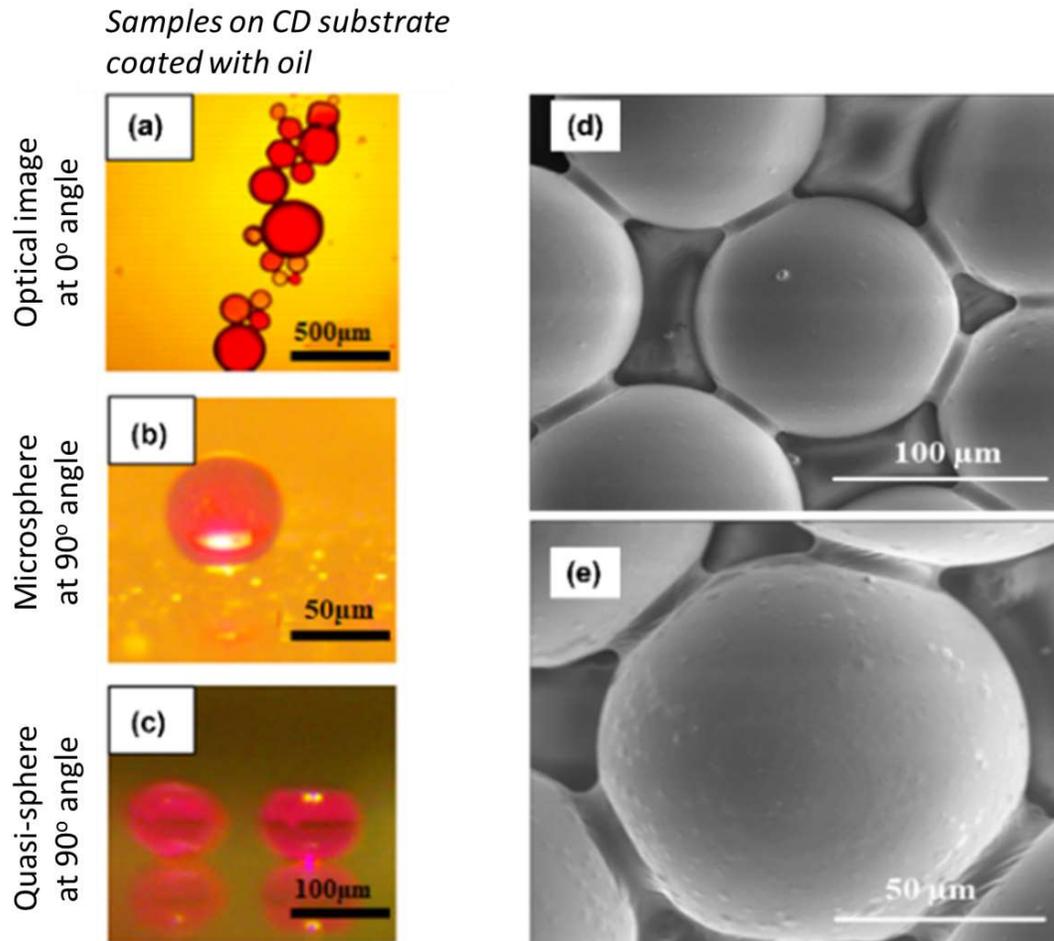
3.1. *Optical images and SEM images*

Fig. 3. (a), (b), (c) Optical images of fabricated microsphere and quasi-sphere samples on a cooking-oil-coated CD. The 0° angle corresponds to the orientation where the glass slide is parallel to the microscope stage. (d), (e) SEM images of microspheres at different magnifications.

Figure 3a shows BSA/RhB microspheres and micro quasi-spheres of various sizes clearly formed on the oil-coated CD surface, exhibiting symmetrical shapes and good surface quality. The side-view image (Fig. 3b) confirms the spherical geometry of the BSA/RhB microsphere, with a smooth surface and preserved shape during drying. The micro quasi-spheres sample at 90° angle (Fig. 3c) shows two well-defined micro quasi-spheres with flattened yet slightly spherical profiles. Their morphology suggests that a thinner oil layer during deposition promotes the formation of quasi-spherical structures rather than spheres.

Figures 3d, 3e show SEM images of several microresonators (top view), which are predominantly spherical in shape with various sizes (Fig. 3d). At a higher magnification (Fig. 3e), the surface morphology is more clearly observed, revealing that it is not entirely smooth and contains small, non-uniform dots. This phenomenon may result from the premature solidification of BSA before all the water vapor has been completely evaporated. While these observations suggest that the fabrication process is not yet fully optimized, and further refinement will be necessary in future studies to improve surface quality and overall performance, they demonstrate that our simple, low-cost, and heating-free method has successfully produced micro resonators of reasonable quality.

3.2. Investigation of laser emission from microsphere and micro quasi-sphere samples fabricated on oil-coated CDs

Laser emission spectra from the fabricated microsphere and micro quasi-sphere samples are shown in Fig. 4. As seen in Figs. 4a and 4c, the microspheres exhibited superior lasing performance, characterized by well-defined laser spectra. To distinguish lasing from WGM-enhanced fluorescence, both intensity behavior and spectral features were analyzed. The input–output curve in Fig. 4b and Fig. 4d shows a clear nonlinear "kink": at low pump energies, the output follows a shallow slope, while above a threshold, the intensity rises much more steeply, indicating the onset of stimulated emission. Above the threshold, the emission linewidth narrows significantly compared with the fluorescence regime, and the lasing peak remains spectrally stable under increasing pump, in contrast to fluorescence-coupled WGM modes, which are typically broader and less stable.

For microsphere lasing emission investigation, a 73 μm diameter microsphere exhibited a low lasing threshold of approximately 1.53 μJ/pulse, with sharp and intense resonance modes and a narrow linewidth of about 0.23 nm in the 610–640 nm wavelength range (Fig. 4a). The free spectral range (FSR) of this sample is approximately 0.96 nm, which agrees well with the theoretical value of 0.91nm calculated by the formula:

$$FSR = \frac{\lambda^2}{2\pi nR},$$

where λ is the wavelength of emission light, n is the refractive index of the cavity medium, and R is the radius of the microsphere. Here, we use a refractive index of 1.36 for the resonant medium, and R is 73 μm. The optical microscopy images (Fig. 3b) show that the dimensions of these microspheres appear uniform in both the horizontal and vertical directions. These results confirm that whispering gallery mode (WGM) lasing is the dominant mechanism in this micro-resonator configuration. The corresponding quality factor (Q) was estimated to be approximately 2833, meeting the requirements for biological microlaser cavities.

For the fabricated micro quasi-sphere, the structure had a diameter of 97.8 μm on top view (Fig. 4d) and a lasing threshold of 3 μJ/pulse (Fig. 4c). Resonance modes appeared in the 600–630 nm range with a linewidth of about 0.73 nm and an FSR of approximately 2.14 nm. The experimentally observed FSR is greater than the theoretical value of 0.678 nm, calculated for $R = 97.8$ μm. This difference is attributed to geometric anisotropy and lower structural quality of the quasi-spheres. Imperfections and nonuniformities in the resonator can broaden or merge closely spaced modes, resulting in an apparently greater FSR. This geometric anisotropy not only causes irregular mode spacing but can also shift the central wavelength of the emission, as the
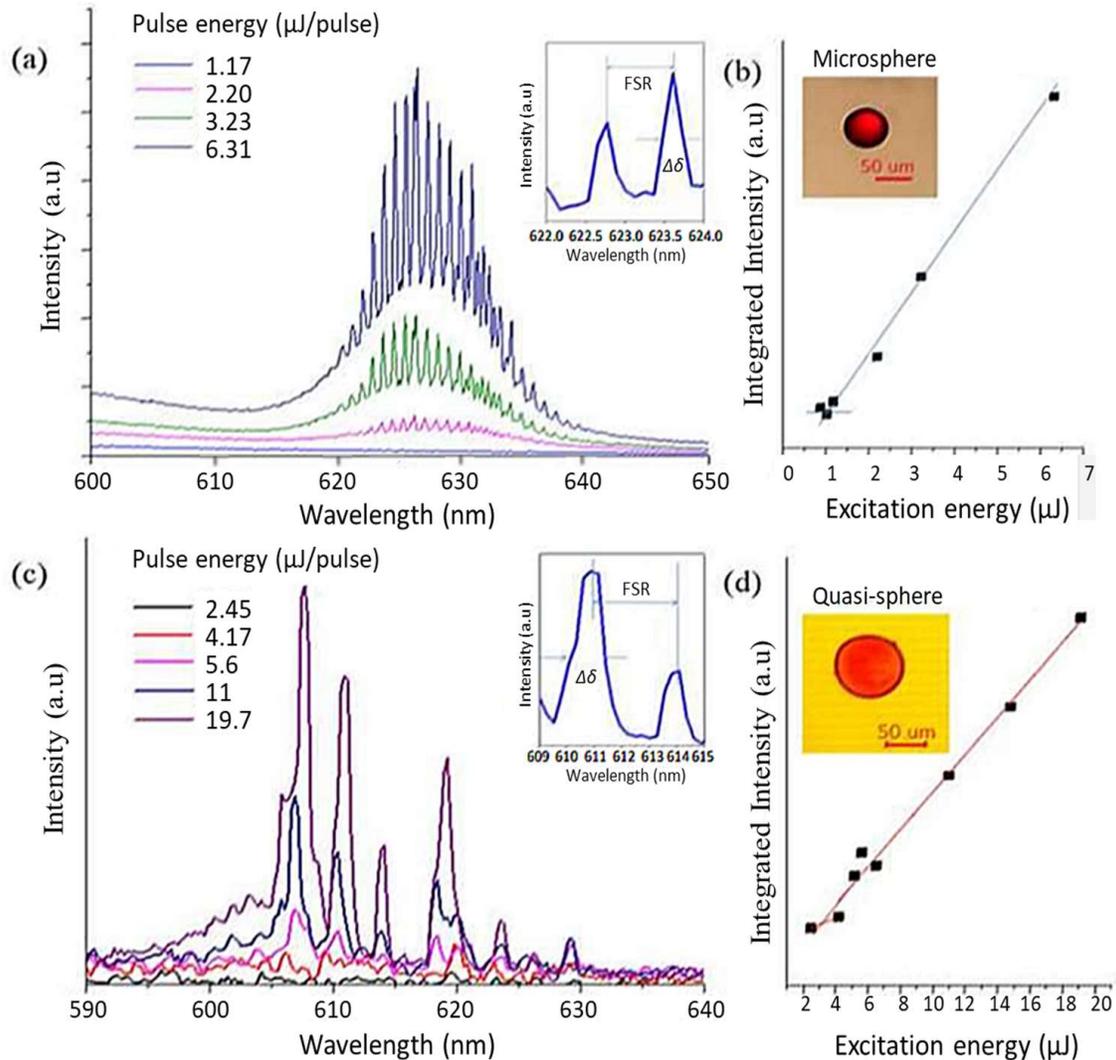
Fig. 4. (Color online) (a), (c) Laser emission spectra and (b), (d) integral intensity spectra as a function of excitation energy of the fabricated microspheres and quasi-spheres, respectively.

WGM resonance wavelength depends directly on the cavity radius [17,18]. Consequently, WGMs from different optical paths may overlap or mix together, producing the irregular mode spacing and wavelength variations observed in the emission spectra. These findings suggest that further optimization of the fabrication process is necessary to improve the morphological uniformity and optical performance of the micro quasi-spheres. The lasing threshold of the quasi-spherical micro resonator is also slightly higher than that of the spherical microsphere, even though its diameter is larger. This can be attributed to the geometric anisotropy and surface irregularities, which reduce the effective optical confinement and gain [19,20].

The operational lifetime of our organic microlasers is mainly determined by the photostability of the organic material, the pump intensity, and the surrounding environment. Under the current pumping conditions, the lasers maintained stable emission for about 15–20 minutes before showing noticeable degradation. With improved encapsulation and optimized pump conditions, the operational lifetime could be further extended.

4. Conclusion

We successfully demonstrated the fabrication of whispering gallery mode (WGM) microlasers in the form of microspheres and micro quasi-spheres using a biocompatible solution composed of BSA and Rhodamine B. The production process used commercially available CDs coated with edible oil, providing a simple, low-cost, chemical-free solution that eliminated the need for costly instruments. This method enables the creation of well-defined optical resonators while maintaining biological safety using natural, non-toxic materials. Optical characterization of the fabricated structures confirmed distinct laser emission with low thresholds (~1 to 3 μJ/pulse) and high quality factors (Q) of up to 2883. These promising results demonstrate the potential of this platform for developing environmentally friendly, cost-effective microlasers applicable in biosensing, intracellular monitoring, and future non-invasive diagnostic technologies.

Acknowledgements

Authors contributions

Hanh Hong Mai designed the experimental study, coordinated the project, prepared and revised the manuscript. Tran Anh Duc, Van Anh Nguyen and Nguyen Minh Nguyet performed the laboratory experiments, collected the data, and prepared the manuscript. Cao Dinh Son, Quang Loc Do conducted the final data analysis and prepared the figures. Mai Thuy Quynh, Pham Van Thanh contributed to the optimization of experimental protocols, assisted with data acquisition, and performed preliminary analyses. All authors contributed to the interpretation of results, drafted or revised the manuscript critically for important intellectual content, and approved the final version for publication.

Conflict of Interest

The authors declare that they have no competing interests related to this work.

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