Delivery of picosecond lasers in multimode fibers for coherent anti-Stokes Raman scattering imaging

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Abstract: We investigated the possibility of using standard commercial multimode fibers (MMF), Corning SMF28 fibers, to deliver picosecond excitation lasers for coherent anti-Stokes Raman scattering (CARS) imaging. We theoretically and/or experimentally analyzed issues associated with the fiber delivery, such as dispersion length, walk-off length, nonlinear length, average threshold power for self-phase modulations, and four-wave mixing (FWM). These analyses can also be applied to other types of fibers. We found that FWM signals are generated in MMF, but they can be filtered out using a long-pass filter for CARS imaging. Finally, we demonstrated that MMF can be used for delivery of picosecond excitation lasers in the CARS imaging system without any degradation of image quality.

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of ultrafast pulses for CARS imaging. Compared to SMFs and PCFs, step-index MMFs have difficulty and instability of laser coupling as well as small coupling efficiencies (<30%). Large mode area PCFs have an aperture (NA) of ~0.06 for large mode area PCF), the numerical aperture (NA) of PCF is usually small (e.g. ~0.06 for large mode area PCF) and, thus, results in difficulty and instability of laser coupling as well as small coupling efficiencies (<30%) [11]. To address these issues, multimode fibers (MMF) may be a good candidate for delivery in microendoscopy applications [11–14]. Therefore, the goal is to develop a flexible, stable, and attention, because of its flexibility for optical alignments as well as the importance for in vivo imaging has been demonstrated as a powerful tool for label-free optical imaging. This technique offers many advantages including (a) chemically selective contrasts based on Raman vibrational activity, (b) high sensitivity and rapid acquisition rates due to the coherent nature of the CARS process, (c) and sub-wavelength spatial resolution [1,2]. Because of its highly-directional coherent property, the CARS signal is several orders of magnitude stronger than the conventional Raman signal; therefore, CARS offers ultrafast imaging capability in video rate in vivo [3]. In addition, the CARS signal is generated only at the laser focus, enabling point-by-point three-dimensional imaging for 3D sectioning without a confocal aperture. As a result, CARS microscopy has been successfully applied to imaging viruses, cells, tissues, and live animals, using signals from CH_2 vibrational activity, (b) high sensitivity and rapid acquisition rates due to the coherent nature of the CARS process, (c) and sub-wavelength spatial resolution [1,2]. 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larger core diameters, larger NA, and larger coupling efficiency. In spite of these advantages, the delivery of two ultrafast pulses in the multimode fiber for CARS imaging has not been investigated.

In this manuscript, we investigated the possibility of using standard commercial MMF, Corning SMF28 fibers, to deliver picosecond excitation lasers for CARS imaging. We theoretically and/or experimentally analyzed issues associated with the fiber delivery, such as dispersion length, walk-off length, nonlinear length, average threshold power for self-phase modulations, and four-wave mixing (FWM). These analyses can also be applied to other types of fibers. We found that FWM signals are generated in MMF, but it can be filtered out by a long-pass filter for CARS imaging. Finally, we demonstrated that MMF can be used for delivery of picosecond excitation lasers without any degradation of CARS image quality.

2. Materials and methods

The schematic of our CARS microscopy system is shown in Fig. 1. The light source was a broadly tunable picosecond optical parametric oscillator (OPO) based on a periodically poled KTiOPO4 crystal (Levante, APE, Berlin). The OPO was pumped by the second harmonic (532 nm) output of a mode-locked Nd:YVO4 laser (High-Q Laser, Hohenems, Austria). The laser delivered a 7-ps, 76-MHz pulse train at both 532 nm and 1064 nm. The 1064 nm pulse train was used as the Stokes wave. The 5-ps OPO signal was used as the pump wave with a tunable wavelength ranging from 670 nm to 980 nm. The beating frequency between the pump and Stokes beams covered the entire chemically important vibrational frequency range of 100–3700 cm$^{-1}$. The pump and Stokes beams were overlapped by a time-delay line and lenses in both temporal and spatial domains to satisfy the precondition for producing a CARS signal. The narrow-bandwidth pump and Stokes pulses ($\sim$3.5 cm$^{-1}$) with durations of 5 ps were able to effectively reduce the non-resonant CARS background [10], and thus ensured a high signal-to-background ratio as well as a sufficient spectral resolution. Meanwhile, the light source also provided excellent power stability, allowing high-sensitivity ultrafast imaging. The microscopy system was modified from a FV300 confocal laser scanning microscope (Olympus, Japan). The modified microscopy subsystem had three PMT detection channels. They were able to detect backward (Epi) CARS signals, forward CARS signals and Rayleigh scattering transmission signals, which was used as a reference. In our experiment, the pump and Stokes beams were coupled into the fiber using a 10 × (NA = 0.25, Newport) microscopy objective and then collimated using another 10 × objective. The dichroic mirror (DM2) used in the microscope was 770dcr from Chroma Technology Corp. The bandpass filter before PMTs was hq660/40m-2p from Chroma Technology Corp. A 1.2-NA water immersion objective lens (60, IR UPlanApo, Olympus, Melville, NJ) was used, yielding a CARS resolution of ~0.4 µm in the lateral plane and ~0.9 µm in the axial direction.

The standard communication fiber, Corning SMF28 optical fibers was used in our experiments. The SMF28 worked as a MMF below its cutoff wavelength of ~1260nm, and covered our CARS operating wavelength range (i.e. from 500nm to 1100nm). It had a core diameter of ~9.2µm and a NA of 0.14. Because its V-parameter was ~4.34 for 817nm (pump) and ~3.33 for 1064nm (Stokes), there were approximately 9 core modes for 817nm and 6 core modes for 1064nm based on calculated results from an estimation equation ($N=V^2/2$) [19]. In our experiments, the coupling efficiency was about 72% for the pump (817nm) and 64% for the Stokes (1064nm), which were coupled into the SMF28 using a 10 × objective. The autocorrelator used to measure auto/cross-correlation function curves was an autocorrelator for APE Levante Emerald OPO (High-Q Laser, Hohenems, Austria). The optical spectrometer used to measure the optical spectra was 86142B optical spectrum analyzer (Agilent Technologies Corp., USA) and HR4000 (Oceanoptics Inc., USA).
3. Theoretical analyses

We started analyses of the fiber design with several important parameters: dispersion length $L_D$ (length over which the duration of a pulse width is broaden by $\sqrt{2}$), walk-off length $L_w$ (length over which two pulses at two different wavelengths are separated in time by one pulse duration), nonlinear length $L_{NL}$ (length over which the SPM-induced phase shift of a pulse equals $2\pi$). Definition in reference 20 was modified to be identical to that in reference 21), and average threshold power, $P_{2\pi}$, for SPM (power at which the SPM-induced phase shift of a pulse equals $2\pi$, and it can be derived from $L_{NL}$ [20,21]. In our study, we considered only step-index fibers for simplicity. These parameters were estimated using Eq. (1a) to (1d) as follows:

$$L_D = \left( \frac{2\pi c}{\lambda^2} \right) \left( \frac{i_r^2}{D} \right). \quad (1a)$$
where $t_p$ was the pulse width, $D$ was the dispersion of the fiber waveguide, $c$ was the speed of light, $\lambda$ was the central wavelength of the pulse, $v_g$ was the group velocity of the fiber mode ($v_g = c/(n-\lambda\cdot dn/d\lambda)$, $n$ is effective index of fiber modes; 20], $n_2$ was the nonlinear refractive index of the fiber material [$n_2 = 2.6 \times 10^{-16}$ cm$^2$/W for silica; 12,20,21], $P_{ave}$ was the average power of the pulse in the fiber, $D_{eff}$ was the effective mode diameter, and $f_p$ was the repetition rate of the laser (76 MHz in our study). For the analyses and experiments presented in this manuscript, the pump and Stokes wavelengths were tuned to 817 nm and 1064nm, respectively, resulting in a 2845 cm$^{-1}$ Stokes shift, which matched with the Stokes shift of the CH$_2$ stretch vibration in lipids [3].

One concern in the design of a fiber delivery system was the broadening of pulse width due to dispersion from the fiber. Pulse broadening leads to a lower effective peak power and would decrease the excitation efficiency of CARS. Although, a pre-chirp unit or a piece of dispersion compensation fiber can be used to compensate for dispersion, the wavelength-
dependence of dispersion still makes it complicated to achieve the optimal design of a compensation unit. In CARS imaging systems, the typical wavelength of interest ranges from 500nm to 1100nm, covering wavelengths from the anti-Stokes wave to the Stokes wave. The typical pulse width of interest ranges from 10fs to 10ps. Figure 2(a) shows calculated \( L_D \) as a function of wavelength (black curve, \( t_p = 5ps \)) and pulse width (red curve, \( \lambda = 817nm \)) in the typical ranges using Eq. (1a), respectively. \( D \) was calculated using an equation in the datasheet of the Corning SMF28 Optical Fibers \( D = S_0/4(\lambda-\lambda_0^2/\partial^2) \), zero dispersion wavelength \( \lambda_0 = 1310nm \). Since the Corning’s equation only covered the intramodal chromatic dispersion (material dispersion and waveguide dispersion) of the fiber but not intermodal dispersion, the intermodal dispersion was simulated using the Sellmeier’s equation and the step-index fiber model [22]. It was noticed that \( L_D \) increased nonlinearly with wavelength or pulse width. At \( t_p = 5ps \), the shortest \( L_D \) was about 11.2 meters at 500nm, which was much longer than the physical fiber length needed for a fiber delivery system. Hence, the dispersion issue was negligible in our imaging system. Meanwhile, \( L_D \) was about 1 meter for \( t_p = 1.08ps \) at \( \lambda = 817nm \). It suggested that the dispersion was not an issue when the pulse width was longer than one picosecond for SMF28.

To calculate the walk-off length \( L_{w} \), the Sellmeier’s equation was employed to simulate the refractive index of the fiber core and the fiber cladding with 1% index difference [19,22]. \( L_w \) defined the extra time delay needed to add to the pump or the Stokes waves to keep their temporal overlapping and to generate CARS signals. Possible shortest and longest \( L_w \) induced by the group velocity difference between the pump and the Stokes waves were estimated as well. Because the effective indices of fiber modes is lower than the core index and higher than the cladding index regardless of SMFs or MMFs, the core and cladding index could be used to estimate the largest and smallest effective index of the fiber modes. In addition, because the wavelengths of interest were in the normal dispersion region (group index decreases as wavelength increases), the group velocity \( v_g \) of the fiber mode increased with wavelength [19]. Since the Stokes wavelength is longer than the pump wavelength, \( v_g \) of the Stokes wave was greater than that of the pump wave. Therefore, when \( v_g \) of the Stokes and pump waves reached their own maximum and minimum respectively, the largest group velocity difference would be obtained and would result in the shortest \( L_w \). Based on our simulations, when the core and cladding indices were used as the effective indices of the pump wave and Stokes wave separately, we could reach the largest group velocity difference between the pump and Stokes waves for MMFs and thus the shortest \( L_w \). On the other hand, SMFs possessed the longest \( L_w \) because there was only a fundamental mode in the fiber and no intermodal dispersions. Based on our simulations, the cladding index was used as the effective index of the fundamental mode to reach the longest \( L_w \). The shortest and longest \( L_w \) were calculated as a function of Raman shift with respective to the Stokes wave, which was assumed to be 1064nm with \( t_p = 8ps \) (for comparison to experimental results). Figure 2(b) shows simulated results using Eq. (1b), where the x-axis Raman shift wavenumber was limited to 4000 cm\(^{-1}\). In addition, \( L_w \) was only plotted up to 3 meter to cover practical fiber delivery interest. It was noted that \( L_w \) decreased as Raman shift increased, and SMFs provided a much larger \( L_w \) than MMFs, especially for Raman shifts within 1200 cm\(^{-1}\). For practical SMFs and MMFs, \( L_w \) fell in the region between the shortest \( L_w \) curve and the longest \( L_w \) curve. Compared to the single \( L_w \) curve of SMFs, \( L_w \) of MMFs existed as an area between the two curves due to cross-calculations of \( L_w \) between different modes. Hence, MMFs had a larger delay adjustment range than SMFs to obtain the optimal temporal overlapping of pump and Stokes waves (i.e. SMFs had an optimal delay adjustment point, while MMF may have an optimal delay adjustment range instead). This effect was confirmed in our experiments using SMF and MMF. To increase \( L_w \), laser pulses with larger \( t_p \) can be used since \( L_w \) is linearly proportional to \( t_p \). Conversely, \( L_w \) will be much shorter when fs laser pulses are used for CARS imaging. Additionally, because the core index (i.e. upper limit of effective index) and the cladding index (i.e. lower limit of effective index) were used as the largest and smallest effective index of fiber modes in our simulations, the shortest \( L_w \) presented in Fig. 2(b) reached the limiting point for MMF and thus was independent of the number of modes propagating in MMF.

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For fiber delivery of ultrafast laser pulses, nonlinear effects (e.g. SPM and FWM) are critical issues, which could either reshape the spectra of laser pulses or generate new laser frequencies [20]. To address these concerns, we estimated SPM induced nonlinear length $L_{NL}$ and average threshold power $P_{2\pi}$ which were induced by SPM in this section. The FWM effect was also investigated in our experiments due to the complicity and significance to estimate FWM originated from interactions between different core modes in MMF [23,24]. In our calculations, we estimated $L_{NL}$ as a function of the mode diameter using Eq. (1c), assuming $f_p$ was 76 MHz, $t_p$ was 5 ps when $\lambda$ was 817 nm and $t_p$ was 10 ps when $\lambda$ was 1064 nm. The solid and the dashed curves in Fig. 2(c) represent different $L_{NL}$ when $P_{ave} = 20$mW and $P_{ave} = 100$mW, respectively. We noted that $L_{NL}$ increased with the mode diameter quadratically, indicating that the SPM effect would be greatly reduced with the increase of the mode diameter. $L_{NL}$ for $P_{ave} = 20$mW was five times larger than that for $P_{ave} = 100$mW. In our case, when the mode diameter was ~9\(\mu\)m, $L_{NL}$ for 817nm at $P_{ave} = 20$mW and $P_{ave} = 100$mW equaled about 45 meters and 9 meters. $L_{NL}$ for 1064nm at $P_{ave} = 20$mW and $P_{ave} = 100$mW equaled about 100 meters and 20 meters. Additionally, we estimated the average threshold power $P_{2\pi}$ as a function of the mode diameter using Eq. (1d), assuming fiber length equaled to 1 meter, $f_p$ was 76 MHz, $t_p$ was 5 ps when $\lambda$ was 817 nm and $t_p$ was 10 ps when $\lambda$ was 1064 nm. The results were plotted in Fig. 2(c). Similar to $L_{NL}$, we noted that $P_{2\pi}$ increased quadratically with the mode diameter. In Fig. 2, both $L_{NL}$ and $P_{2\pi}$ for 1064nm are larger than those for 817 nm, which is predicted by the Eq. (1c) and (1d).

4. Experimental results and discussions

![Normalized measured autocorrelation function curves of the pump (817nm, 50mW) and the Stokes (1064nm, 50mW) waves at two different conditions: 1. direct output from OPO or laser, and 2. After passing through 2-meter SMF28.](image)

![Normalized measured cross-correlation intensity curves before and after the pump (817nm) and Stokes (1064nm) waves passed though a 2-meter SMF28.](image)

In our experiments, we examined the dispersion-induced broadening of the pulse width using SMF28, whose core diameter was 9.2 \(\mu\)m and cladding diameter was 125 \(\mu\)m. We measured the autocorrelation function curves of the pump (817nm, 50mW) and the Stokes (1064nm, 50mW) waves at two different conditions: (1) direct output from the OPO or laser, and (2) after passing through a 2-meter SMF28. The normalized autocorrelation curves were shown in Fig. 3(a). By measuring the FWHM bandwidth of the curves, we calculated the percentage of pulse broadening per meter: 7.2% per meter for 817nm and 3.8% per meter for 1064nm. Based on the results shown in Fig. 2(a) ($L_D = 21.07$m for 817nm, $L_D = 41.24$m for 1064nm), the calculated percentage of pulse broadening was 6.7% per meter for 817nm and 3.4% per meter for 1064nm, which were about 6.9% and 10% smaller than the measured ones. This discrepancy could be caused by the step-index fiber model used in simulations, which utilized weakly-guiding and scalar mode approximations. In addition, the discrepancy could also arise from measurement errors, as well as possible difference between the real fiber parameters and
those used in simulations. In spite of this discrepancy, the broadening effect of the pulses was still negligible by using MMFs for the fiber delivery in CARS imaging.

![Fig. 4](image)  
(a) Normalized measured pump (817nm) wave spectra as a function of power in SMF28; (b) Normalized measured Stokes (1064nm) wave spectra as a function of power in SMF28; (c) Normalized measured FWM (663nm) wave spectrum output from SMF28.

We examined the walk-off length $L_w$ by measuring the cross-correlation function curves before and after passing through an 2-meter SMF28. A strong Gaussian-shape single peak of cross-correlation function curve indicated that the pump (817nm) and the Stokes (1064nm) waves achieved a good overlapping in time without any walk-off; otherwise there would be small shoulders. After the two waves passed the 2-meter SMF28, we adjusted the translation stage of the delay line to obtain the strongest Gaussian-shape single peak again. Then, we calculated the adjustment amount of the translation stage of the delay line. This amount value corresponded to the walk-off induced delay in distance by the SMF28. The normalized cross-correlation intensity curves, before and after passing through a 2-meter SMF28, are shown in Fig. 3(b). Adjustment for the 2-meter SMF28 was 1.607 mm or 53.56 ps (26.78 ps/meter). Because the measured FWHM pulse width of 817nm and 1064nm pulses were 5.647ps and 10.47ps, we took the average (~8ps) of the pulse width to calculate the measured $L_w$. Then, the measured $L_w$ was 0.2987 meters for 8-ps pulse and 2-meter SMF28. Based on our simulated $L_w$ in Fig. 2(b), the simulated shortest $L_w$ for MMF, which was 0.2578 meters for 2845cm$^{-1}$ Raman shift, corresponding to the pump (817nm) and Stokes (1064nm) waves. Therefore, our measured $L_w$ result was longer than the simulated shortest $L_w$, which fell in the region between the simulated longest $L_w$ and the simulated shortest $L_w$ shown in Fig. 2(b).

We examined the SPM effect induced by the pump (817nm) and Stokes (1064nm) waves propagating in a 1-meter SMF28. Within the power range from 0 to 200mW used in our experiments, we did not observe the cross-phase modulation (XPM) effect (i.e. no spectral change) when both the pump and Stokes waves propagated in the fiber simultaneously. Hence, we measured the spectrum with either the pump or Stokes wave propagating in the fiber separately. Figure 4 illustrates normalized measured pump (817nm) and Stokes
wave spectra as a function of propagating power in SMF28. We noted that there were some ripples in spectra of pump (817 nm) waves. It originated from the artifact effect of the 2nd order grating inside the grating-based Agilent OSA, which was confirmed by changing the grating option in the OSA configuration and the technical supporting staff of the Agilent Corp. Another artifact effect of the grating-based Agilent OSA was that when the input $\lambda < 850$ nm, the OSA display showed both $\lambda$ and $2\lambda$, which was described in Agilent OSA application notes and it is important for FWM measurements. In Fig. 4(a), we noted that FWHM bandwidth of pump waves increased with power. At 200 mW, the FWHM bandwidth broadened by ~36.8%, but it was still far from $2\pi$ phase shifts (peak splitting in central wavelength) [20]. The power of 200mW exceeded the average power, i.e. less than tens of milliwatts, usually applied in CARS microscopy. In Fig. 4(b), we noted that FWHM bandwidth of Stokes waves also increased with power. At 200 mW, FWHM bandwidth broadened by ~31.3%, which was far from $2\pi$ phase shifts as well. Results in Fig. 4 indicated that the 1-meter SMF28 can be used to deliver individual pump or Stokes waves without generating serious SPM-induced phase shifts.

Next, we examined the FWM effect induced by the pump (817 nm) and Stokes (1064 nm) waves simultaneously propagating in a 1-meter long SMF28. We found weak anti-Stokes generations at 663 nm, which matched the 2845 cm$^{-1}$ anti-Stokes shift of the CH$_2$ stretch vibration. Therefore, it would result in spurious CARS signals and background noise in the imaging system. The zero-dispersion wavelength of fibers plays an important role in the FWM behavior [25,26]. For SMF, the FWM phase-matching condition is difficult to be met for the frequency components shifted by more than 3000 cm$^{-1}$ from zero dispersion wavelength of the fiber [25,26]. However for MMF, the FWM phase-matching condition is relaxed by the easiness of satisfying the phase-matching condition with pump, Stokes and anti-Stokes waves which propagate in different modes [23,24]. For instance, the anti-Stokes wave at the fiber mode $LP_{21}$ can be generated by the combination of the pump ($LP_{01}$), the pump ($LP_{02}$) and the Stokes ($LP_{11}$) [23,24]. As a result, more fiber modes exist in the fiber, more diverse mode combinations will exist to satisfy the FWM phase-matching condition, generating stronger FWM signals. Thus, MMF is more likely to satisfy the phase-matching condition to generate the FWM signals than SMF. In our case, although the anti-Stokes (663 nm, ~7450 cm$^{-1}$) wavelength was far away from the zero dispersion wavelength of the SMF28 (i.e. 1310 nm), SMF28 can still easily satisfy the FWM phase-matching condition because there were approximately 9 fiber modes for 817 nm and 6 fiber modes for 1064 nm existing in SMF28. Figure 4(c) shows a typical normalized measured FWM (663 nm) wave spectrum output from a 1-meter long SMF28. In our experiment, a clear peak was observed at 663 nm while no other new peaks occurred when the pump (817 nm) and Stokes (1064 nm) waves propagated in SMF28 simultaneously. Also, we noted that anti-Stokes signals (663 nm) was quadratically proportional to the input power of the pump (817 nm) and linearly proportional to the power of the Stokes (1064 nm). We need to point out that the FWM signal was measured using an optical spectrometer HR4000 (Oceanoptics, Inc), which provided better sensitivity than Agilent OSA in the range of visible wavelengths.

In addition, we verified the FWM effect using our CARS microscopy. Instead of inserting the 1-meter SMF28 before the entrance of the CARS microscopy, we mounted it directly under the 10 × (NA = 0.25, Newport) objective and captured the backward FWM (or nonresonant CARS) images from the proximal end of the fiber. The Epi-CARS channel was used with a bandpass filter (hq660/40m-2p, Chroma Technology Corp). Powers of the pump and the Stokes at the proximal end of MMF were 200 mW and 100 mW, respectively. Figure 5 shows a brightfield image of the well-cleaved proximal end of a 1-meter SMF28 and five CARS images from the proximal end of the 1-meter SMF28 at various conditions, such as pump plus Stokes, pump only, distal end suspending in air or immersing in water/oil, and well-cleaved or bad-cleaved distal end. We observed strong FWM signals emerging from the fiber core when the pump (817 nm) and Stokes (1064 nm) waves were coupled simultaneously into the SMF28 as shown in Fig. 5(b). The circular pattern of the FWM signals indicated the mode distribution in the core of the SMF28 was not uniform. No FWM signal was detected...
when only the pump wave (817nm) was coupled into the SMF28 as shown in Fig. 5(c). There were weak FWM signals when the well-cleaved distal end of the SMF28 was immersed in water [Fig. 5(d)] or oil [Fig. 5(e)] or when the distal end was bad-cleaved/cut [Fig. 5(f)]. Collectively, these findings suggested that the FWM signals were mainly generated in the forward direction.

Fig. 5. (a) Brightfield image of the well-cleaved proximal end of a 1-meter long SMF28; CARS images from proximal end of the 1-meter SMF28 at (b) 817nm + 1064nm and well-cleaved distal end suspending in air; (c) 817nm only and well-cleaved distal end suspending in air; (d) 817nm + 1064nm and well-cleaved distal end immersing in water; (e) 817nm + 1064nm and well-cleaved distal end immersing in oil; (f) 817nm + 1064nm and bad-cleaved/bad-cut distal end suspending in air.

Finally, we tested the SMF28 to deliver ps lasers for CARS imaging. The setup is shown in Fig. 1. Emerging from the dichroic mirror (DM1), the pump (817nm) and Stokes (1064nm) waves were coupled into a 1-meter long SMF28 by a 10 × Newport objective. After passing the fiber, the two waves were then collimated by another 20 × Newport objective. A 750nm long-pass filter (FEL0750, Thorlabs Inc.) was used to eliminate the FWM (663nm) signals generated in the SMF28 before the microscopy system. The pump and the Stokes waves were tuned to 40 mW and 20 mW for CARS imaging. We characterized the performance of the setup by imaging calibrated 10µm polystyrene beads (PEB), which generated strong resonant CARS signals at the aliphatic symmetric CH2 stretch (Δω = 2845cm⁻¹). Figures 6(a) and 6(b) show the forward and Epi CARS images of 10µm polystyrene beads spin-coated on a glass slide by delivering ps lasers through a 1-meter SMF28. The CARS images were verified by the results of single pump wave taken at 2845cm⁻¹. In Fig. 6(b), the Epi-CARS image clearly showed the characteristic ring structure of PEBs due to the relative large size of PEBs compared to the small coherence length of Epi CARS signals. In terms of the CARS image quality, such as contrast and resolution, no clear difference was noticed between using free-space and using a 1-meter SMF28 for delivery of the laser. To further assess the performance of delivering ps lasers through the SMF28 fiber, we imaged two types of mouse tissues ex vivo. Figures 6(c) and 6(d) show the Epi CARS images of the mouse kidney and ear, respectively. There were no discernable degradations with regard to the image quality obtained through fiber delivery compared to free-space delivery [3]. In addition, we tested the
stability of this SMF28 fiber-delivered CARS system by characterizing fluctuations of the CARS signal while imaging PEBs. The fluctuations of the CARS signal are 1.5% and 4.6% for the short-term (i.e. one-hour) and the long-term (i.e. two-day), respectively. These results demonstrated that the SMF28 can be used to deliver ps lasers for CARS imaging, and a filter can be used to block the FWM signals generated in the fiber.

Fig. 6. CARS images were captured by CARS system with delivery of ps lasers through SMF28. Forward (a) and Epi (b) CARS images of 10 µm polystyrene beads spin-coated on a glass slide, scale bar is 5 µm. Epi CARS images of (c) mouse kidney and (d) mouse ear, scale bar is 10 µm.

5. Conclusion

According to our theoretical and experimental analyses, we found that the dispersion of fibers is not an important issue for the design of a fiber delivery system. The reason is that the dispersion length of the fibers is much longer than the physical length of the fibers used for laser delivery in a CARS imaging system. Because of the group velocity difference between the pump and Stokes waves traveling in the fibers, the delay line needs a certain amount of adjustment to compensate for the walk-off length between the two beams. Based on our analyses on the nonlinear length and the average threshold power for SPM, it suggests that fibers with larger effective mode diameters can be used to decrease SPM-induced phase shifts of the laser pulses. There are FWM signals at the anti-Stokes frequency generated in the SMF28. These signals mainly propagate in the forward direction. A long-pass filter can be used to filter out the FWM signals to eliminate spurious CARS signals and background noise.
in the system. Thus, according to our investigations, SMF28 fibers can be used for delivery of picosecond excitation lasers in a CARS imaging system without any degradation of the image quality.

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