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A direct modulated optical link for MRI RF receive coil interconnection

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Abstract

Optical glass fiber is a promising alternative to traditional coaxial cables for MRI RF receive coil interconnection to avoid any crosstalk and electromagnetic interference between multiple channels. A direct modulated optical link is proposed for MRI coil interconnection in this paper. The link performances of power gain, frequency response and dynamic range are measured. Phantom and *in vivo* human head images have been demonstrated by the connection of this direct modulated optical link to a head coil on a 0.3 T MRI scanner for the first time. Comparable image qualities to coaxial cable link verify the feasibility of using the optical link for imaging with minor modification on the existing scanners. This optical link could also be easily extended for multi-channel array interconnections at high field of 1.5 T.

Keywords: Direct modulation; Radio frequency (RF) coil; Signal-to-noise ratio (SNR); Dynamic range

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1. Introduction

In recent years, RF arrays with multiple coil elements ranging from 32, 64 to 96 have been successfully demonstrated [1–3]. However, with the rapid increase of coil numbers, the crosstalk between coaxial cables and connectors becomes more serious and deteriorates the image qualities. Greater risk of RF burn due to the cable ground loops is also a threat to patience safety. In additional to these electronic problems, mechanical bulk and stiffness of the cables represent a limitation on the ease of operation.

Baluns and cable traps are usually conventional solutions to some of the electromagnetic (EM) problem. However, patterns of shield current on the cables are much dependent on their placement, length, grounding and coupling to the magnet environment. Therefore, absolute characteristics of shield currents become difficult to be predicted accurately. Accordingly, the placement of cable traps should also be optimized for each specific setting.

Optical glass fiber could be a promising alternative to coaxial cables for the MRI coil array interconnection to avoid EM problems completely. Because there are only optical signals transmitted, glass fiber is naturally immune to electromagnetic interference. And for the same reason, all earth grounds can be removed from the coils. Also, optical fiber has very broad bandwidth to carry a huge amount of data, analog or digital ones, with very low attenuation to maintain the signal intensity during transmission. Small cross section, light weight and mechanical flexibility of fiber make it easy to handle with. Costs of optical elements and devices are greatly reduced during these years.

A suitable optical link for MRI coil interconnection is expected to have an adjustable power gain to control the signal intensity. A flat frequency response over a wide frequency range is also desired to make the optical link possible for use at different field strengths. And low noise figure (NF) is required to avoid introducing much noise during optical transmission and reception. In addition, MRI signals often have very wide dynamic range. Therefore, a very large linear range is required for an optical link to transmit signals with the same amplification. Meanwhile, intermodulation terms should be also minimized to avoid distortion.

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A fiber-optic link always includes three primary components of an optical transmitter, a glass fiber cable and an optical receiver. In transmitter, the optical output is modulated by the input RF signal. This modulated optical signal is transmitted through the fiber and converted back into the electrical RF signal in the receiver. Optical modulation method determines the overall link performance. There are usually two modulation methods: direct modulation and external modulation. The architectures of a direct modulation link and an external modulation link are illustrated in Fig. 1(a) and (b), respectively. In general, a direct modulated optical link has simpler structure than an external modulated one. By eliminating the expensive optical modulator such as Mach–Zehnder modulator, the cost of a direct modulated optical link could reduce by more than 80% without sacrificing overall optical link performances [6]. The detail comparison between direct and external optical modulation has been demonstrated by authors in the previous work [6]. An external modulated optical link used for MRI coil connection has been demonstrated by Koste et al. [7]. In this paper, we focus on the analysis of the direct modulation method for MRI and demonstrate the first use of a direct modulation optical link at 0.3 T low field MRI to verify its applicability.

2. Methods

2.1. Link structure overview

An analog direct modulated optical link was built and the structure of the optical transmitter and the receiver are shown in Fig. 2 and Fig. 3, respectively. In the optical transmitter, the input RF signal is first amplified by a low noise preamplifier made by ourselves. A second stage amplifier could be provided for additional RF power amplification if needed. To avoid too much RF power input, a RF protection circuit is included. A 1 mW 1330 nm Fabry–Perot (F–P) laser diode (LD) is used in the optical transmitter to convert the RF signal into optical output. The automatic power control (APC) circuit is used to eliminate the laser output variation due to the temperature shift. In the optical receiver, the input optical signal is first converted back into electrical RF signal by a photo diode (PD), then pre-amplified and low-pass filtered. Variable attenuators are used in the receiver to adjust the power of the output RF signal depending on the requirement for power gain, noise figure and dynamic range. The photodiode used in the optical receiver has the linearity from r from −112 to 2 dBm. The optical transmitter and receiver are connected by a single mode optical fiber using FC/APC connectors.

2.2. Link performance evaluation

The overall link performances are evaluated by the power gain, frequency response, SNR and dynamic range in this paper for MRI applications. These four parameters are measured in a bench test using an HP 8595E spectrum analyzer. Two HP 8647A signal generators are used as the RF signal sources in the bench test.

The intrinsic power gain g_i of an ideal optical link without power loss in the fiber, can be written by Eq. (1) [8]:

$$g_i = s_l^2 r_d^2, \tag{1}$$

where s_l is the slope efficiency of the LD, and r_d is the responsivity of the PD. The slope efficiency and responsivity are 0.15 W/A and 0.85 A/W, respectively, thus the intrinsic power gain should be about −18 dB. This power attenuation of −18 dB is determined by the low power conversion efficiency of the LD and PD between electrical and

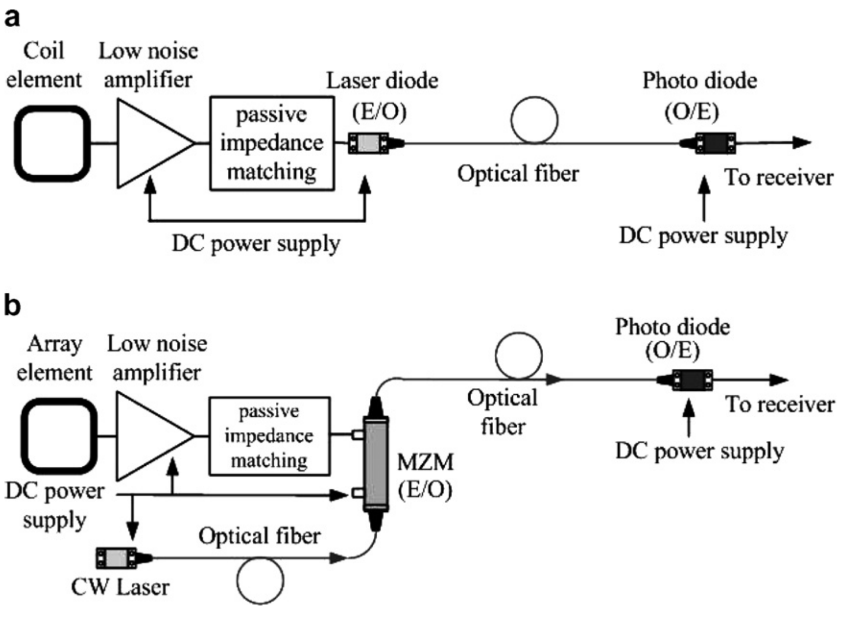

Fig. 1. Optical link structures of (a) a direct modulated link by an LD, and (b) an external modulated link by a Mach–Zehnder modulator (MZM).

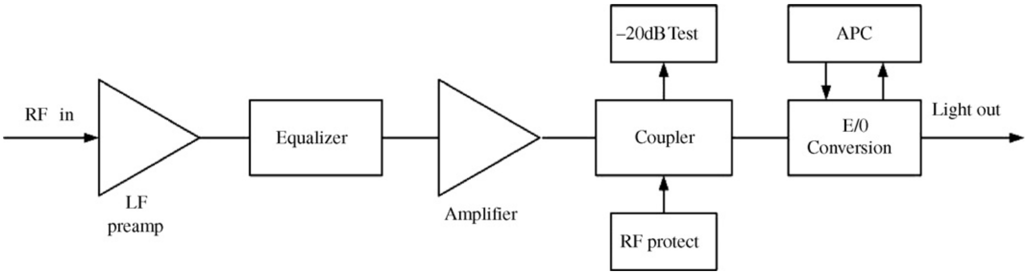

Fig. 2. Structure diagram of the optical transmitter in the direct modulated optical link.

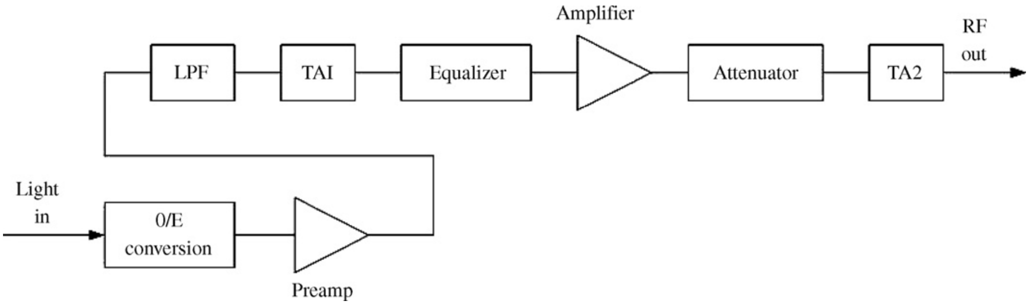

Fig. 3. Structure diagram of the optical receiver in the direct modulated optical link.

optical signals. It indicates most of the RF power is dissipated in the electrical/optical (E/O) signal conversion during modulation and O/E conversion during demodulation. Accordingly, amplifiers have to be used to compensate the RF power dissipation in the optical link. Because it is hard to obtain more than 30 dB out of a single amplifier without getting instability, more than one gain stage may be required in the optical link depending on the specific situation. Since variable attenuators are used in the optical receiver, the total power gain of the link is adjustable.

In theory, the range of frequencies over which an optical fiber link could transmit is determined by the bandwidth of the optical transmitter and receiver, also by the dispersion of the fiber. The typical bandwidth of an optical link is in the microwave range of GHz, much higher than the resonant frequencies of all current MRI systems. However, in reality, the frequency response of a practical optical link is determined more by electrical components like filters rather than optical components.

The noise sources in a pure optical link include relative intensity noise (RIN) from the LD, shot noise from the PD. In a direct modulated optical link, the laser RIN is usually the dominant noise source. The intrinsic link noise figure (NF) can be written in Eq. (2) [8]:

$$\mathrm{NF_{RIN}} = 10\log\left(2 + \frac{I_\mathrm{D}^2 10^{\frac{\mathrm{RIN}}{10}} R_\mathrm{LOAD}}{2 s_1^2 r_\mathrm{d}^2 kT}\right)(\mathrm{dB}), \tag{2}$$

where I_D is the average PD current, RIN is in dB, R_LOAD is the load resistance, k is the Boltzmann's constant of 1.38×10^{-23} J/K and T is the absolute temperature. Note that the intrinsic link NF is only valid for the condition that there are no amplifiers or attenuators in the link. The laser RIN is about −150 dB/Hz in our optical transmitter. Thus the estimated link NF is about 29 dB according to Eq. (2), much higher than the critical requirement of less than 1 dB for MRI. This high intrinsic NF has to be compensated by the insertion of the low noise preamplifiers in the optical link.

The Friis's formula as written in Eq. (3) shows the dependence of the total noise factor of a cascade link on the power gain and noise factor of each stage cascade component.

$$\mathrm{nf_{total}} = \mathrm{nf}_1 + \frac{\mathrm{nf}_2 - 1}{g_1} + \frac{\mathrm{nf}_3 - 1}{g_1 g_2} + \frac{\mathrm{nf}_4 - 1}{g_1 g_2 g_3} + \cdots \tag{3}$$

In Eq. (3), nf_n is the noise factor of the nth stage component in the cascade link, and g_n is the power gain of the nth stage component. It is obvious that the first stage NF of the cascade link would dominate the total NF if its power gain g_1 is high enough. Therefore, a low noise preamplifier with 25 dB power gain and 1 dB NF is used in the optical transmitter. Actually, the preamplifer on the RF receiver coil, which also has high power gain and very low NF, usually acts as the first stage in the total gain chain during scan. With the combination of the second stage power gain on the optical link, the total power gain chain provides a very low NF to satisfy the imaging SNR requirement.

The noise floor of an optical link determines the minimum detectable RF signal. Non-linearities in the laser and amplifiers tend to limit the maximum RF signal. The 1 dB compression point is generally used to specify the dynamic range when signal tone is transmitted in the link. However, because a large number of signals with different frequencies are transmitted through the links, the 3rd order intermodulation free dynamic range (IMF3) and the 3rd order intercept point (IP3) are used to specify the link dynamic range. The IMF3 is the output power difference of fundamental and the 3rd order intermodulation (IM) terms in dB when the 3rd order IM power is just equal to the noise floor. Usually IMF3 is normalized to the noise floor with 1 Hz bandwidth. Values of 1 Hz-normalized IMF3 and IP3 are related by the following equation

$$\mathrm{IMF3}_{1\ \mathrm{Hz}} = \frac{2}{3}(\mathrm{IP3} - N_{1\ \mathrm{Hz}}), \tag{4}$$

where $N_{1\ \mathrm{Hz}}$ is the system noise floor with the bandwidth of 1 Hz. For signal transmission with bandwidth of Δf, the IMF3 is calculated by the following equation

$$\mathrm{IMF3} = \mathrm{IMF3}_{1\ \mathrm{Hz}} - 10\log\frac{\Delta f}{1\ \mathrm{Hz}}. \tag{5}$$

The 3rd order intermodulation (IM) terms should be controlled below the link noise floor to avoid any distortion caused by the higher amplification ratio to 3rd order IM terms than to fundamental terms.

2.3. Imaging experiments on a 0.3 T MRI system

The direct modulated optical link is used for a saline phantom imaging and *in vivo* human head imaging on a XinAoMDT 0.3T vertical low-field MRI system (Lanfang, Hebei, China) at the resonant frequency of 12.64 MHz. A commercial receive-only head RF coil for this low field system, also provided by XinAoMDT, is used for imaging. The input of the optical transmitter is directly connected to the output of the preamplifier on the RF coil. Due to the magnetic susceptibility, the optical transmitter is placed out of the main magnet but near to the head RF coil as closed as possible. Thus there is still a short length of coaxial cable about 20 cm between the coil output and the optical transmitter input. The output of the optical transmitter output is connected by a 10-m fiber to replace the coaxial cable in the screening room. The fiber passes through the penetration panel on the wall, and the other end is connected to the optical receiver placed outside of the screening room. Finally, the output of the optical receiver is connected to the input of the RF receiver on the penetration panel by a coaxial cable. The scanning parameters setup for phantom and head imaging are listed in Table 1. Link performances are evaluated by the comparison of images obtained by the optical link with those by electrical cable links.

Table 1
Scanning parameters for phantom and *in vivo* human head imaging

	Phantom	Head
Image orientation	Axial	Saggital
Pulse sequence	2D spin echo	2D spin echo
Number of excitation (NEX)	2	2
Flip angle (FA)	90°	90°
TR/TE (ms)	400/19	400/25
FOV (mm)	260 × 260	260 × 260
Matrix size	256 × 224	256 × 128
Number of slice	12	1
Slice thickness/gap (mm)	8.0/2.0	6.0/1.0
Acquisition time (s)	179	51

3. Results

3.1. Bench test

The noise floor of the spectrum analyzer is about −76 dBm when its internal receiver bandwidth is set as 10 kHz. The power gain of the optical link is shown in Fig. 4 when the variable attenuator is adjusted to its maximum. As seen from Fig. 4, the power gain of the optical link is about 9 dB. The linear region of the link is from input power of −75 to −20 dBm, which means the power gain of the link remains constant without compression in this input power level range. If the input power is higher than −20 dB, the power gain of the link begins to compress, and distortion occurs in signal transmission due to the different power gains for input powers with different levels. It can be also seen in Fig. 4 that the 1 dB compression point appears at input power of −18 dBm, where the power gain is about 8 dB. When the variable attenuator is adjusted to minimum, the power gain of the link is about 29 dB but the linear region does not change. Thus the power gain of the direct modulated optical link is adjustable in a 20 dB range from 9 to 29 dB.

The dependence of the link power gain on frequency is measured from 10 to 85 MHz with the constant input power of −25 dBm. The measurement result is shown in Fig. 5. The frequency response curve of the optical link is almost flat from 5 to 80 MHz, in which region the link power gain maintains around 9 dB within a 0.3 dB fluctuation. According to the Larmor equation, this frequency response indicates the optical link could be used for MRI systems from 0.25 to 1.5 T.

In the measurement of IMF3 of the optical link, two HP 8647A signal generators are used to generate two equal-amplitude RF signals with a small frequency interval of

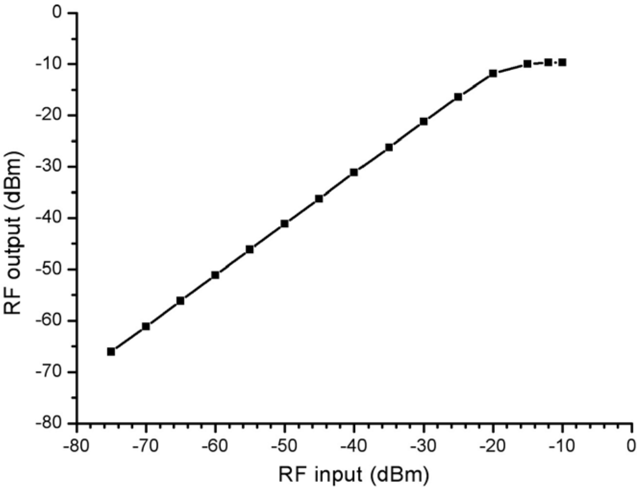

Fig. 4. The power gain and the linear region of the optical link.

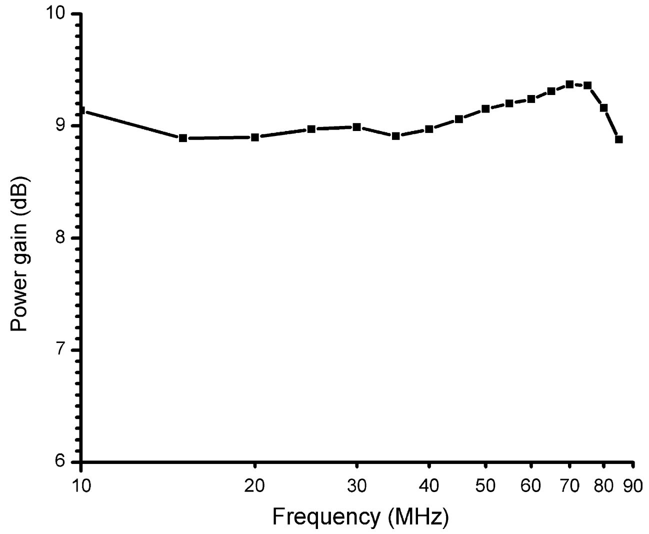

Fig. 5. Frequency dependent power gain of the optical link from 10 to 90 MHz with constant input RF power of −25 dBm.

200 kHz, i.e. 30.4 and 30.6 MHz in this measurement. Then the two 3rd order IM terms occurs at 30.2 MHz and 30.8 MHz, respectively. Because these two 3rd order IM terms are very near the fundamental RF signal, it is difficult to get rid of them by a filter. Therefore, these 3rd order IM terms should be kept below the noise floor to avoid signal distortion.

During the measurement, the input power of the two channel RF signals is increased gradually until the output of the 3rd order IM terms is higher than the noise floor. The internal receiver bandwidth of the spectrum analyzer is set as 10 kHz. The noise floor is about −76 dBm in this measurement. The magnitudes of the fundamental output and 3rd order IM output with the increase of input RF power are plotted in Fig. 6. If we extend the curves of the fundamental and the 3rd order IM terms within their linear regions in Fig. 6, the input power at which these two curves intersect is called the 3rd order intercept point (IP3). Actually, for most of practical links, both the fundamental and the 3rd order IM curves have been in the compression region at IP3, so IP3 is just an ideal parameter for measure of link dynamic range. It is found in Fig. 6 that the *IMF*3 of the optical link is measured to be about 45 dB with 10 kHz receiver bandwidth of spectrum analyzer. According to Eq. (5), $\mathrm{IMF3}_{1\ \mathrm{Hz}}$ of the optical link should be 85 dB with receiver bandwidth of 1 Hz as in Fig. 6. However, when we tried to reduce the receiver bandwidth of the spectrum analyzer, its noise floor did not reduce according to the scaling law of noise power. It indicates this measurement result of 45 dB IMF3 is restricted by the −76 dBm noise floor of the spectrum analyzer. Any signal with intensity less than −76 dBm could not been detected in the measurement.

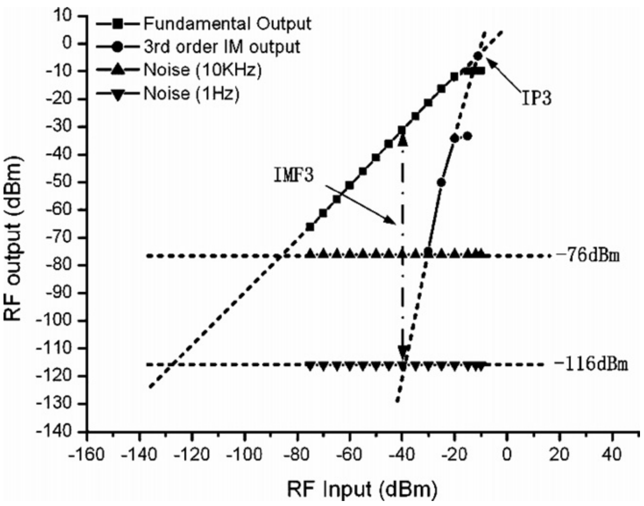

Fig. 6. Third order intermodulation free dynamic range and 3rd order interception point of the direct modulated optical link.

3.2. Imaging experiments

Phantom images obtained by the electrical coaxial cable and optical fiber link are shown in Fig. 7(a) and (b), respectively.

The intensities of the phantom images in Fig. 7 mapped by SNR are compared. The noise region is selected as the whole background in the images. The signal region is selected as the circle just covering the phantom. The result shows that SNR of the phantom image obtained by the coaxial cable is about 5% higher than that obtained by the optical fiber. This means the optical link adds just a few noises in the transmission, and the SNR performance of the optical link is comparable with that of the coaxial cable link.

The *in vivo* human head images (from slice 1 to slice 9) obtained by the electrical coaxial cable and optical fiber link are shown in Fig. 8(a) and (b), respectively. Although no obvious distortion is observed in the images by optical link, there is actually blurring and slight SNR reduction in those images when compared to those by coaxial cable. Therefore, the performance of the direct modulated optical link should be further improved to meet the critical requirement for clinical applications.

4. Discussion

Different from the bench test, the low noise preamplifier on the RF receive head coil acts as the first stage amplifier in the imaging experiment, with 30 dB power gain and 1 dB NF; while the low noise preamplifier on the optical transmitter acts as the second stage amplifier, with 25 dB power gain and 1 dB NF. According to Eq. (3), the total link NF should be nearly the noise figure of the preamp, that is, 1 dB, which indicates few additional noise is introduced into the transmission by the optical link. However, 5% SNR reduction was observed in the phantom image comparison between the cable link and the optical link. Some blurring was also found in both phantom and *in vivo* head images by the optical link. This SNR reduction may be

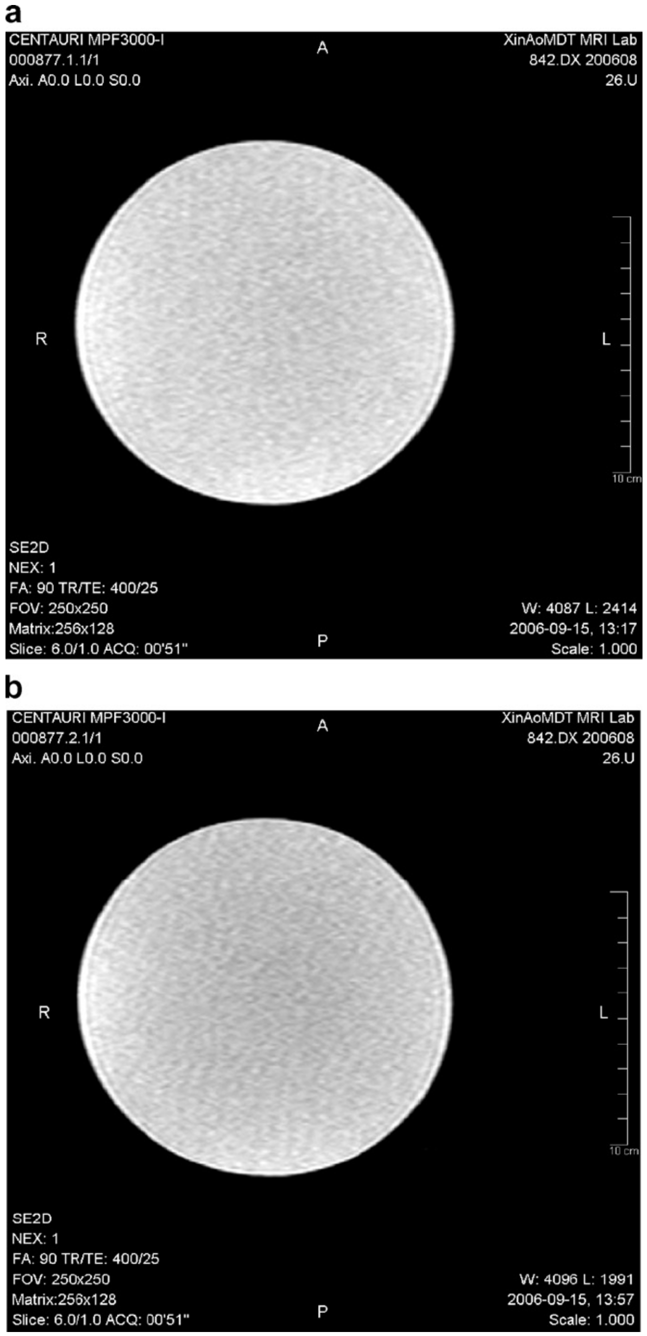

Fig. 7. The phantom images obtained by (a) electrical coaxial cable link, and by (b) optical fiber link.

caused by the signal saturation at the output at the preamp on the optical transmitter. After 30 dB amplification by the first stage preamp, the MR signal at the input of the preamp on the optical transmitter may exceed its linear range, so fractions of MR signal is not amplified proportionally through the second stage preamp and this leads to the SNR reduction and blurring in the reconstructed images.

On the other hand, because preamplifiers usually achieve low NF by mismatch, its input impedance is not 50 Ω any more. This is fine for the first stage preamplifier. However, a low NF preamplifier with mismatched impedance is also used in the optical transmitter, the power reflection will reduce gain in the imaging. Additional amplifier as shown in Fig. 2 after the LF preamp could be used to compensate the power reflection.

Therefore, preamp design is critical to address the SNR issue. Cascade amplifiers and attenuators should be carefully chosen and optimized in the total link design. In the future design, using only one low NF preamplifier should be better if the optical transmitter circuit could be integrated on the coil itself.

As mentioned in the results section, the narrow IMF3 measurement result of 45 dB is restricted by the noise floor of the spectrum analyzer. The actual noise floor during the imaging with receiver bandwidth of Δf could be expressed by the following equation

$$N_{\Delta f} = G_t + \mathrm{NF} + 10\log(kT\Delta f/10^{-3}), \tag{6}$$

where NF is the total noise figure of the link, G_t is the total link power gain, k is the Boltzmann's constant and T is the absolute temperature. With typical receiver bandwidth of 500 kHz in the available commercial MRI, the thermal noise floor represented by the last term on the right-hand side in Eq. (6) is about −117 dBm at room temperature of 290 K. The total link NF is 1.3 dB. The total link power gain before the analog-digital converter without the optical link could be set by the MRI scanner from 4 to 46 dB. Thus, the total power gain with the optical link could be set from 13 to 55 dB if the power gain of the optical link alone is set at 9 dB. Accordingly, the noise floor of the analog receiver chain with the optical link during imaging varies from −103 to −61 dB. Then the IMF3 could be calculated by

$$\mathrm{IMF3} = \frac{2}{3}[\mathrm{IP3} - N_{\Delta f}]. \tag{7}$$

With the IP3 of −3 dBm shown in Fig. 6, the dynamic range could vary from 39 to 67 dB. Actually, in many practical applications, only fraction of the full receiver bandwidth is used, e.g. 16 kHz, so the dynamic range of the optical link is expected to be about 77 dB according to Eqs. (6) and (7).

Although the setting of the receiver gain on MRI scanner could be important for dynamic range optimization of the total transmission chain including the optical link, this process could be automatically done by the auto prescan on the scanner in our imaging experiments. This makes the optical link very convenient for immediate imaging just by connection directly to the RF receive coil. There is no distortion found in Fig. 8, which means the optical link works in its linear range and its IMF3 is wide enough for low field application of 0.3 T. However, for high field MRI systems, MRI signals often have much higher dynamic range, for example, as high as 86 dB in power at 3 T [9], or even higher than 100 dB. The dynamic range of the optical link could be further optimized by converting the optical link from a pure power gain link to a power constant link. Thus the total link dynamic range could be improved slightly to about 82 dB at receiver bandwidth

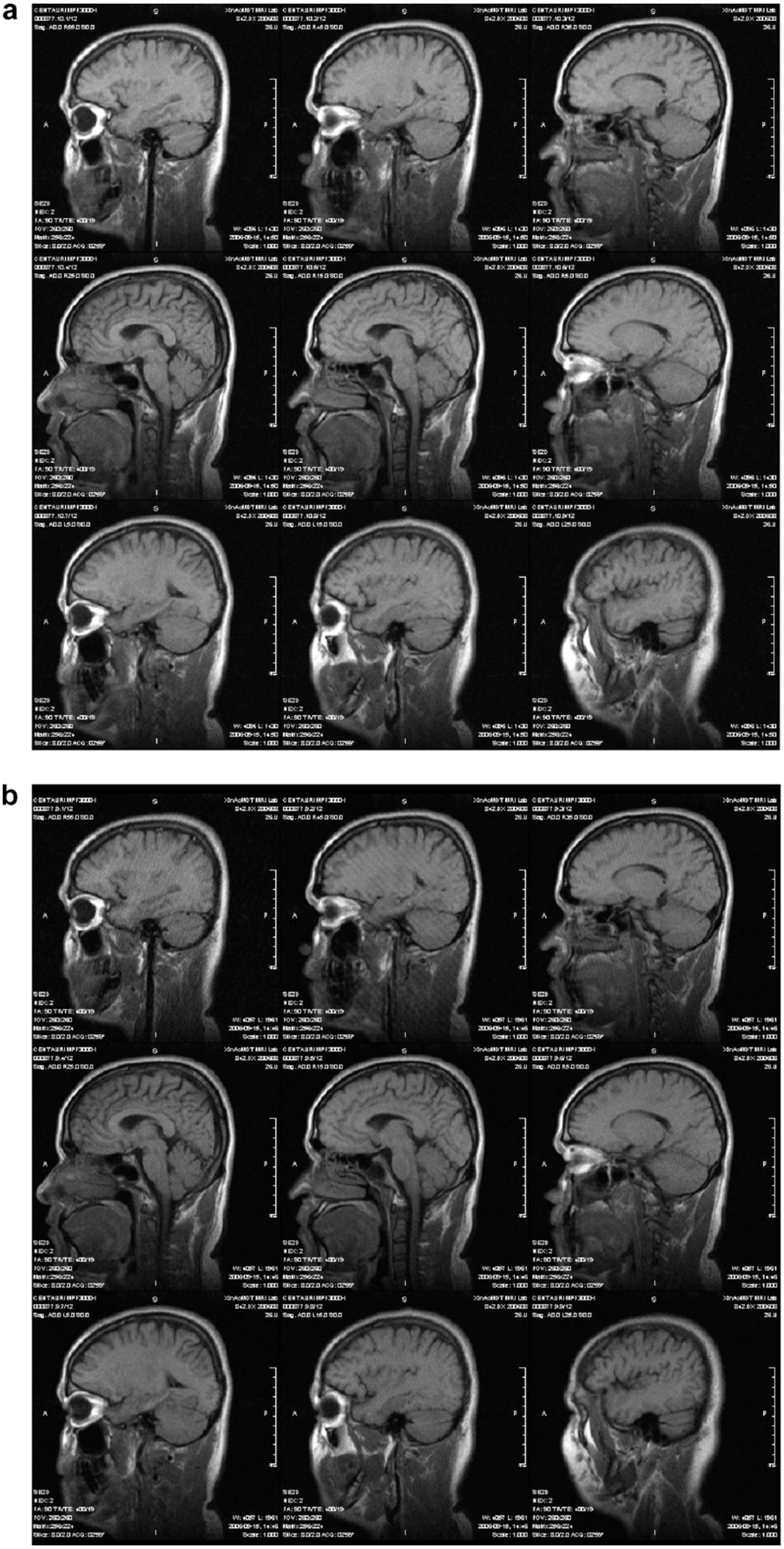

Fig. 8. (a) *In vivo* human head images obtained by the coaxial cable link. (b) *In vivo* human head images obtained by the optical fiber link.

of 16 kHz according to Eqs. (6) and (7). Recently, an analog optical link employing an integrated balanced photodiode (BPD) has been introduced, which could achieve a dynamic range of 102 $dB*Hz^{2/3}$ at 5 GHz [10]. Wider dynamic range could be expected by BPD method at lower frequency [10]. This makes the optical link possible for the potential use at high field MRI, e.g. 3 T or at ultra-high field, whose resonant frequency is still much lower than 1 GHz.

There are still some engineering issues that should be well addressed for the practical use of optical links for MRI. The first one is the magnetic susceptibility. The major materials in LDs are compounds of groups III and V elements, including gallium arsenide, indium phosphide and indium arsenide. Although they are not ferromagnetic materials, it should be further verified if their modulation performance would change in the strong magnetic field. Another problem of the material is that the packages of the commercial optical and electrical components often include iron. Therefore custom-designed non-magnetic components are required for the use of the optical transmitter working in the MRI main magnet.

Direct modulated optical links show more benefits in interconnections for multi-channel array coils. Optical transmitters are required to be integrated into the RF coil elements in this case. For this purpose, the optical transmitter should be built more compact and well EM shielded. We are making more optical transmitters with smaller sizes and a four-channel optical receiver is ready for the future experiment on multi-channel array coils.

Another technical issue associated with the integration is the local DC supply for the optical transmitters. The optical transmitter in current design needs voltages of 5, 15 and 24 V for driving. These voltages are supplied by a DC power remotely through electrical wires. For the purpose of no wires in an optical link to avoid any EM problems, power over fiber (PoF) technology has been demonstrated to convert optical power into DC power as a solution [10], but high power lasers over 1 W are required in this solution due to the low power convert efficiency of the available photovoltaic power converter, about 30–40% [11]. In addition, these high power lasers still need to be electrically driven remotely. We are investigating the optical transmitters with lower driving voltages so that chargeable batteries are possible to be used as a better power solution. A power scavenging circuit has been demonstrated recently for DC power supply for MR wireless transmission. This circuit takes advantage of local, unused transmit RF power and converts it into usable DC power [12]. It is considered to benefit not only wireless transmission but also optical transmission.

5. Conclusion

Optical fiber is proposed to replace coaxial cable for connecting the RF coils and the receivers in MRI scanner because it is naturally immune to electromagnetic interferences. It removes the risk of RF burning due to the ground loops. Fiber is also light and flexible to be easily handled. The optical link has a potential to become a robust solution to the bottle neck in massive parallel receive system.

A direct modulated optical link is designed and built to verify its feasibility for MRI applications. The power gain, frequency response, and dynamic range of the optical link are measured in the bench tests. The direct modulated optical link is also demonstrated for phantom and *in vivo* human head imaging on a 0.3 T MRI system. The phantom image SNR obtained by the optical link is comparable with that by the coaxial cables. The results confirm that the direct modulated optical link is feasible for daily routine imaging with minor revision on the MRI scanner. We believe the direct modulated optical link would show great advantages for multi-channel array interconnection at high field due to the elimination of electrical interferences. A four-channel direct modulated optical link for 1.5 T is being built for this purpose. The future work also includes the better power solution by chargeable batteries and feasibility of optical multiplexing technology for signal transmission in a single fiber for arrays.

Acknowledgments

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