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Pulsed Ferrite Magnetic Field Generator for Through-the-earth Communication Systems for Disaster Situation in Mines

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A pulsed ferrite magnetic field generator (FMFG) was designed for the use in the 1000 m long through-the-earth (TTE) communication system for mining disaster situations. To miniaturize the TTE system, a ferrite core having 10,000 of permeability was used for the FMFG. Attenuation of the magnetic field intensity from the FMFG (200-turn and 0.18 m diameter) was calculated to be 89.95 dB at 1000 m depth soil having 0.1 S/m of conductivity. This attenuation was lower than 151.13 dB attenuation of 1 kHz electromagnetic wave at the same conditions. Therefore, the magnetic-field was found to be desirable as a signal carrier source for TTE communications as compared to the electromagnetic wave. The designed FMFG generates the magnetic field intensity of 1×10^{-10} Tesla at 1000 m depth. This magnetic field is detectable by compact magnetic sensors such as flux gate or magnetic tunneling junction sensor. Therefore, the miniature FMFG TTE communication system can replace the conventional electromagnetic wave carrier type TTE system and allow reliable signal transmission between rescuer and trapped miners.

Keywords : ferrite helical loop antenna, through-the-earth (TTE) communication, ferrite magnetic field generator (FMFG), disaster in mine

1. Introduction

The ratios of coal mine explosion accidents to the total accidents in US mines were recorded to be 68% from 1839 to 2008 by the National Institute for Occupational Safety and Health (NIOSH) [1]. Also, several thousand miners are annually killed by mining disasters in the world. Accordingly, the fast grasping of position and status for the trapped miners is significantly important to increase the number of survivors [2]. In order to respond to the rescue efforts for the mining disaster, various emergency communication systems have been developed [2-7].

There are two communication systems available for the mining industry. One is miner-to-miner (MTM) communication system, while the other one is through-the-earth (TTE) communication system. The MTM communication system allows a long-distance communication between miners via Leaky Feeder [6, 7], Ethernet, WiFi, Medium Frequencies, and Wireless-Mesh-Networks. The Leaky Feeder consists of communication cable, booster (i.e. amplifier and repeater), base station, and 100-200 MHz walkie-talkie. The Leaky Feeder is designed to transmit and receive signals through the communication cable. Therefore, the Leaky Feeder needs line amplifiers and repeaters to compensate for signal losses. Usually, a 40 km long communication cable is managed by one base station. Consequently, the MTM communication can be failed by a damaged cable or base station in disaster situations. Further, the Leaky Feeder requires battery backups for operation in case of the power failures. Therefore, the wired Leaky Feeder is undesired for mining communication system.

In order to address these issues, Flexalert (one-way system used in Canada), PED (one-way system used in Australia), and TeleMag (two-way system used in US) [3] were developed. The Flexalert and PED systems were designed for surface-to-underground communication, i.e. one-way communication system. Accordingly, the surface rescuers cannot receive information about underground

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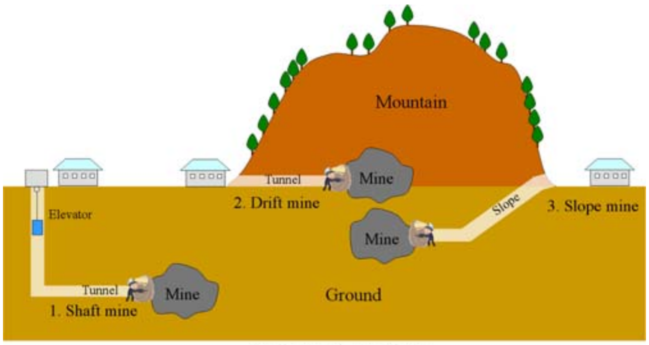
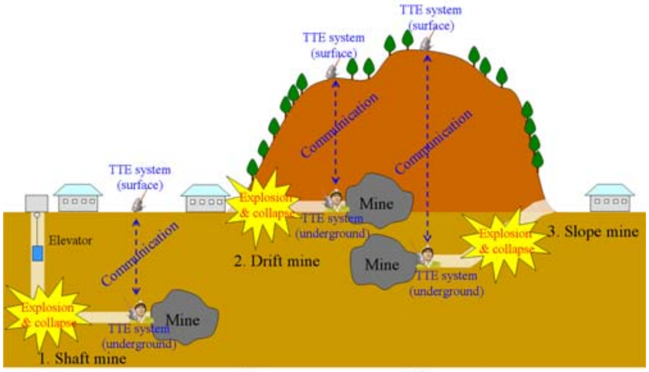


(a) normal condition



(b) emergency condition

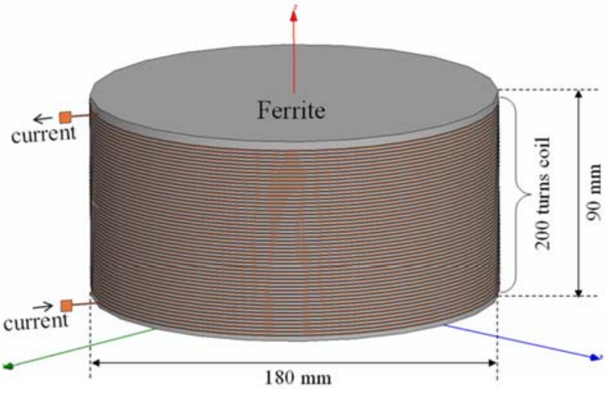
Fig. 1. (Color online) TTE communication systems in mines.

situations from the trapped miners. On the other hand, the TeleMag was designed for two-way communication as shown in Fig. 1(a) and (b). This system uses a 4 kHz electromagnetic (EM) wave transmission. Such a low frequency has small EM attenuation in the soil medium compared to MHz frequencies. It was reported that the 4 kHz TeleMag system was successfully demonstrated for two-way voice communication between surface and underground using a 60-foot (20 m) loop antenna [3-5]. However, the large size of the loop antenna is undesired for the limited space of mine underground. In addition, the EM wave propagation is largely affected by the moisture and conductive materials in the TTE communication environment.

In this paper, we designed a miniature magnetic field generator for two-way TTE communication system. The attenuation properties of magnetic field signal were calculated and reported in comparison with EM wave signal.

2. Design of Ferrite Magnetic Field Generator

Pulsed ferrite magnetic field generator (FMFG) was designed for two-way TTE communication system as presented in Fig. 2. It consisted of a ferrite cylinder, copper coil, current input and output terminals. The copper wire had the diameter of 0.81 mm and 45 μm thick Teflon coated on the wire. The copper wire was then wound counterclockwise around the ferrite cylinder. When electric current flows from input to output terminals, a magnetic field is generated around the coil by the right hand rule. It is known that the generated magnetic field can be intensified by magnetic permeability of the loaded ferrite cylinder. Therefore, high permeability ferrite is desired for the core material. In the designed FMFG, Mn-Zn ferrite was selected due to high permeability of 10,000 and low magnetic loss up to several hundred kHz [8].



Input DC current: 1 A
Turns: 200
Permeability:10,000
Ferrite weight: 11.445 kg (volume: 2289 cm^3)

Fig. 2. (Color online) Designed pulsed ferrite magnetic field generator (FMFG) for TTE communication.

In addition, the designed FMFG utilizes a pulsed magnetic field as a signal source instead of modulated EM waves. The operating frequency of the designed FMFG system is higher than frequency of the voice fundamental (F_0) of 210 Hz [9]. It is noted that magnetic field is unaffected by moisture and conductive materials in the soil medium. On the other hand, the EM waves are significantly attenuated. Therefore, a LC resonant frequency (i.e. LC value of 2.53×10^{-8} for 1 kHz), needs to be avoided for non-resonance operation. Low capacitance (C) is desirable for a given inductance (L). The L was selected to be 46.4 H at 1 kHz. Consequently, capacitance (C) of the designed FMFG required being lower than 0.55 nF at 1 kHz. It is noted that the capacitance is controllable by a dielectric constant of ferrite core and design of helical coil geometry.

3. Results and Discussion

Attenuations of the EM wave and static magnetic field

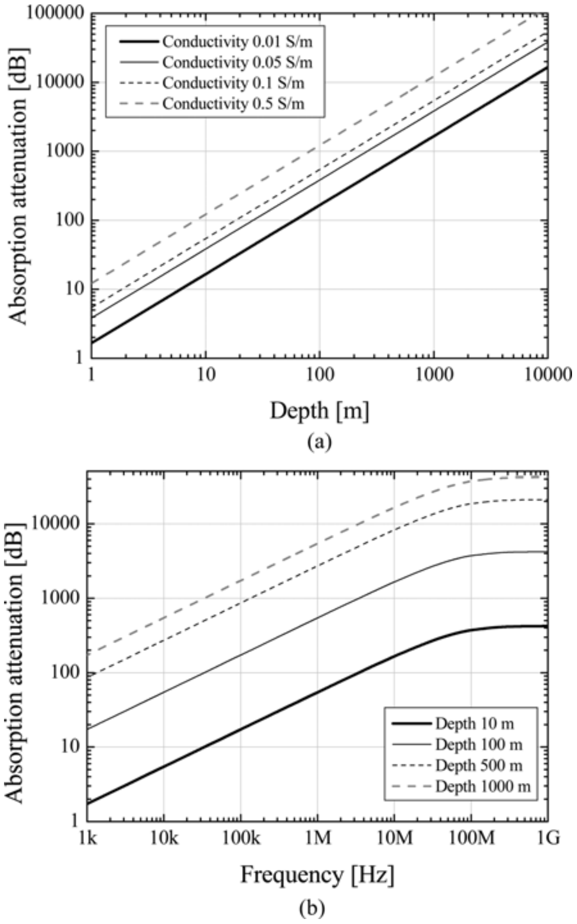


Fig. 3. (a) Depth and (b) frequency dependence of absorption attenuation for the transmitted electromagnetic wave.

were calculated and compared for two-way TTE communication system. Based on the calculation, the design of the FMFG was optimized to improve the signal to noise ratio for the TTE communication.

3.1. Electromagnetic wave transmission

Absorption attenuation of transmitted EM wave in the soil medium can be calculated by Eq. (1) [10].

Absorption loss [*dB*/*m*]

$$= 8.69 \times \omega\sqrt{\mu\varepsilon}\left\{\frac{1}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]\right\}^{0.5} \qquad (1)$$

where ω is angular frequency, μ is the permeability, ε is the permittivity, and σ is conductivity of the soil. Nonlinearity of the soil's electric conductivity [11], permittivity [12], and earth's electromagnetic field [13, 14] has been extensively studied by many geophysics researchers. However, in this calculation, constant material properties of the soil were used for the simplified calculation.

Table 1. Absorption loss and permittivity at 100 MHz of various medium.

	Absorption loss [dB/m]	Permittivity
Air	0	1
Clay	10-100	2-40
Concrete	2-12	4-10
Dry sand	0.01-1	4-6
Fresh water	0.1	80
Soil (Firm)	0.1-2	8-12
Dry soil (Sandy)	0.1-2	4-6
Wet soil (Sandy)	1-5	15-30
Dry soil (Loamy)	0.5-3	4-6
Wet soil (Loamy)	1-6	10-20
Dry soil (Clayey)	0.3-3	4-6
Wet soil (Clayey)	5-30	10-15

Figure 3(a) and (b) show the calculated absorption attenuations of the EM wave as a function of soil depth and carrier frequency, respectively. In the calculation, μ_r of 1 and ε_r of 15 were used for the soil. The calculated absorption attenuation was 5437 dB with 1000 m depth, 0.1 S/m of soil conductivity, and 1 MHz of carrier frequency in Fig. 3(a). It was found that the absorption attenuation increased with increasing conductivity of the soil. This is attributed to a decrease in effective skin depth. As given in Eq. (2), the effective skin depth of the soil is inversely proportional to the root of conductivity [15]. The permittivity and absorption losses of various soils are given in Table 1 [16].

$$\text{Effective skin depth of soil } (\delta) = \frac{1}{2\,\omega\mu_0\sigma} \qquad (2)$$

where μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ T·m/A).

Figure 3(b) shows the calculated absorption attenuation as a function of carrier frequency with 0.1 S/m of soil conductivity. It was noted that the absorption attenuation decreased as the carrier frequency decreased. The absorption attenuation was 172.66 dB with 1 kHz of carrier frequency and 1000 m soil depth.

In order to evaluate the total attenuation, we have also estimated free space path loss (FSPL) [17] of the EM wave. The FSPL was calculated by Eq. (3).

Free space path loss [*dB*]

$$= 20\log_{10}(d) + 20\log_{10}(f) + 32.45 \qquad (3)$$

where d is the depth or distance in km and f is the frequency in MHz. Fig. 4 shows the calculated FSPL as a function of depth at various carrier frequencies. The FSPL for 1 MHz and 1 kHz (not shown) of the carrier frequency were 32.44 dB and –21.53 dB at 1000 m soil

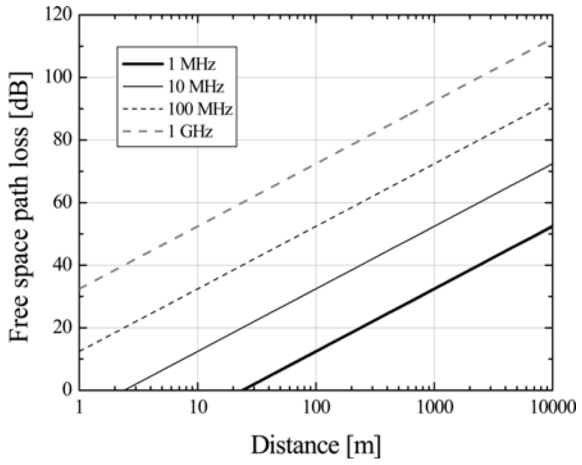


Fig. 4. Distance dependence of free space path loss for various carrier frequencies of the electromagnetic wave.

depth, respectively. Accordingly, the total attenuations of 1 MHz and 1 kHz EM waves through the soil with 0.1 S/m of conductivity were 5468.44 dB and 151.13 dB. In order to receive a 151.13 dB attenuated signal, transmitting power needs to be higher than 1 W, which leads to −121 dBm (7.94×10^{-16} W) of received power. This meets the sensitivity of the conventional super-heterodyne receiver. Therefore, 1 kHz of carrier frequency is desired for the transmission of EM wave through 1000 m soil depth. However, large size of antenna is necessary to resonate at 1 kHz for the EM wave radiation. When one kHz omni-directional antenna is considered, the radius of the antenna is 10.6 km to achieve 100% radiation efficiency according to Chu's theory [18]. It was reported that the 90 m long TTE communication was demonstrated with a 3 MHz helix antenna having the length of 2.06 m and diameter of 0.22 m [19]. The size of the helix antenna is impractical for the underground mine applications. Also, our attenuation calculation showed that EM wave propagation is sensitive to change in conductivity of soil, thereby lowering signal to noise ratio. The current TTE communication systems use the EM wave as a signal carrier source [3-5].

3.2. Magnetic field transmission

To significantly reduce the signal sensitivity to propagation medium and enhance the communication reliability, the pulsed magnetic-field TTE system was designed. Due to the low operating frequency of the designed TTE system, the propagating magnetic field is negligibly influenced by the eddy current loss of the soil. As a result, the magnetic field is advantageous as the signal carrier source over the EM wave for the TTE communication in the coal mine environment.

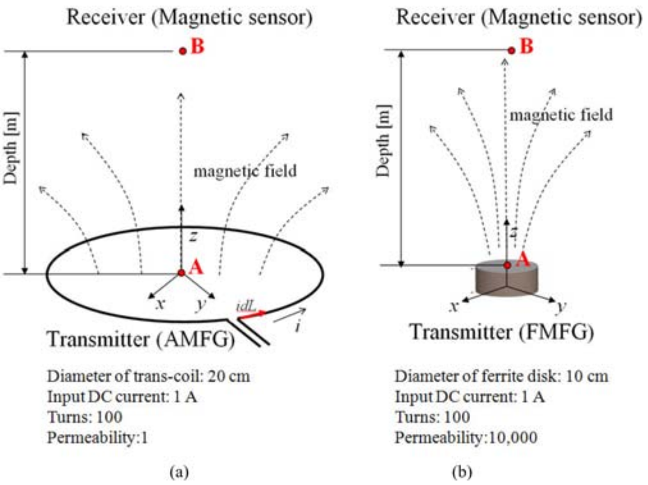


Fig. 5. (Color online) (a) Air-core magnetic field generator and (b) ferrite magnetic field generator systems for the calculation of magnetic field attenuation.

Figure 5(a) and (b) show the schematic constructions of air-core magnetic field generator (AMFG) and FMFG, respectively. Number of helical turn was 100 for both generators. The A and B (in Fig. 5) indicate a transmitting generator and receiving magnetic sensor, respectively. Accordingly, the magnetic field is transmitted from A (transmitting generator) to B (receiving sensor).

In order to compare attenuation characteristics between the AMFG and FMFG, the magnetic field intensity B_A and B_B at A and B positions were calculated by the Eqs. (4) and (5) based on the Biot-Savart law.

$$B_A = \frac{\mu_r \mu_0 N i}{4\pi R^2}\oint dL = \frac{\mu_r \mu_0 N i}{4\pi R^2} 2\pi R = \frac{\mu_r \mu_0 N i}{2R} \tag{4}$$

$$B_B = \frac{\mu_r \mu_0}{4\pi}\frac{2\pi R^2 N i}{(z^2+R^2)^{3/2}} \tag{5}$$

where, i is current, μ_0 is $4\pi \times 10^{-7}$ T·m/A, R is radius of helical coil, and N is number of helical turns. The electrical input source was 1 A and 1 V.

Figure 6(a) and (b) present the depth dependence of the magnetic field intensity for the AMFG and FMFG, respectively. It was found that the magnetic field intensity decreased with increasing the depth. Nevertheless, the FMFG showed much higher magnetic field strength than the AMFG. This is because magnetic permeability of the ferrite core intensified the magnetic field. Therefore, the FMFG transmits stronger magnetic field signal than the AMFG with the same diameter. It was found that one-meter diameter FMFG and AMFG showed the transmitting distance of 2200 m and 110 m, respectively, for 1 ×

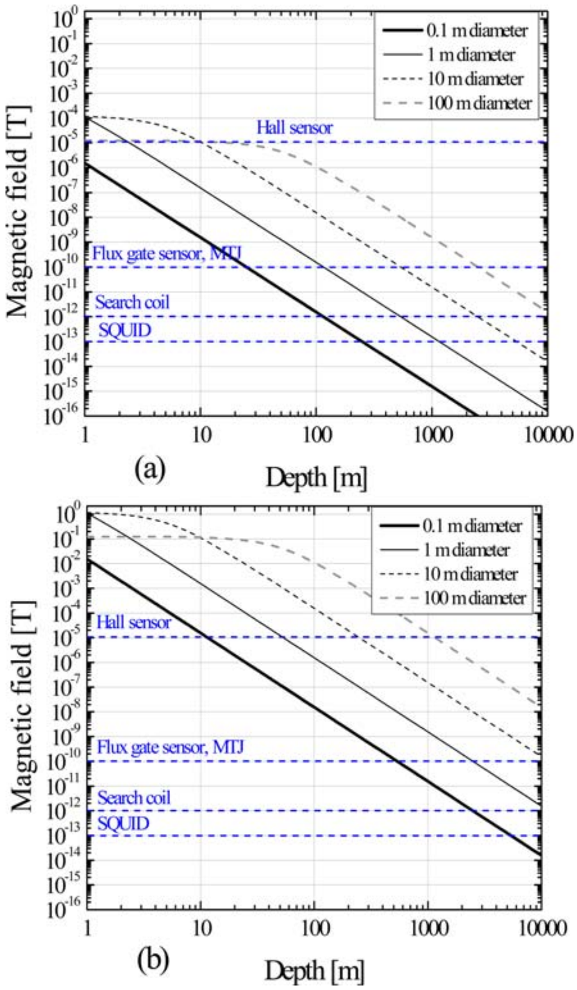


Fig. 6. (Color online) Depth dependence of calculated magnetic field intensity for various diameters of (a) air-core magnetic field generator (permeability = 1) and (b) ferrite magnetic field generator (permeability = 10,000).

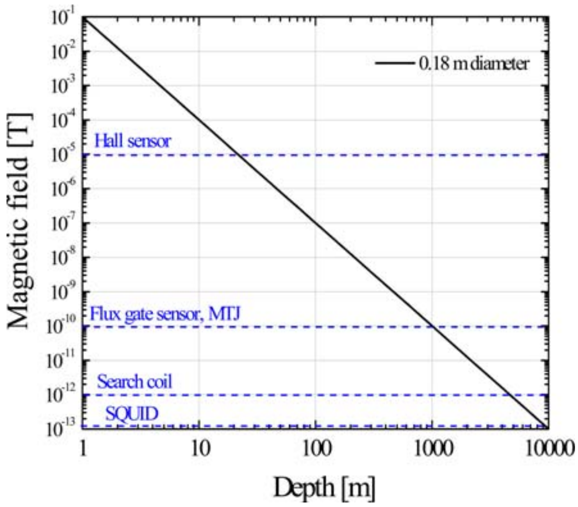


Fig. 7. (Color online) Depth dependence of magnetic field attenuation of optimized ferrite magnetic field generator.

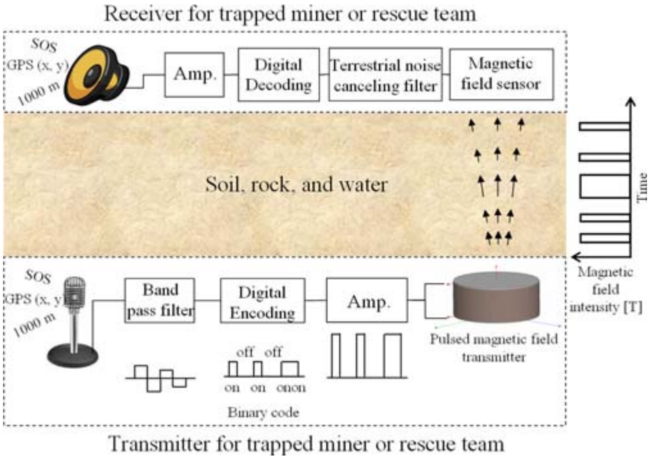


Fig. 8. (Color online) Schematic block diagram of the magnetic field carrier type TTE system.

10^{-10} Tesla of magnetic field intensity. It should be noted that the 1×10^{-10} Tesla magnetic field is detectable by flux gate or magnetic tunneling junction sensor [20, 21]. These sensors are typically used for the gyroscope of navigator and the magnetic head of hard disk, respectively.

Based on the above calculated magnetic field intensity, the diameter and number of helical turns for the FMFG were optimized to be 0.18 m and 200, respectively. Fig. 7 shows the distance dependence of the calculated magnetic field for the optimized FMFG. Magnetic field of 1×10^{-10} Tesla was obtained at 1000 m depth. This can be converted to −89.95 dB of magnetic field intensity. This is higher than −151.13 dB of electromagnetic wave signal intensity with 1 kHz carrier frequency. Accordingly, the FMFG is applicable to 1000 m depth TTE communication system. For comparison with the AMFG, the 17.96 m diameter and 200 turns were required to transmit the same magnetic field intensity of 1×10^{-10} Tesla. Correspondingly, the FMFG size was one hundred times smaller than the AMFG. The use of high permeability ferrite core dramatically reduced antenna size with the same magnetic field intensity at a given depth. High permeability Mn-Zn ferrite is commercially available for the application of the TTE communication systems [8, 22].

Schematic block diagram of the magnetic-field carrier type TTE system is shown in Fig. 8. The TTE system has a FMFG, magnetic-field sensor, amplifiers, filters, noise canceller, speaker and microphone. In the communication, voice signal is converted to a pulsed current and transformed into a pulsed magnetic field as a signal carrier source. At the receiver, a received pulsed magnetic field signal is reconverted to voice signal through noise filter-

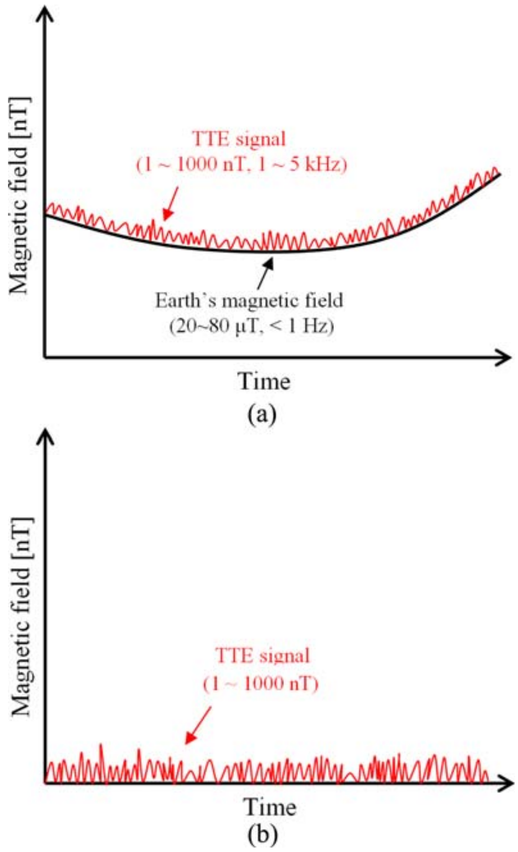


Fig. 9. (Color online) Conceptual magnetic field vs. time graphs of (a) sensed magnetic field signal with earth's magnetic field and (b) corrected magnetic field signal by TTE system.

ing and digital decoding processes.

The sensed magnetic field at a receiver is the sum of generated magnetic field by the FMFG and earth's magnetic field as shown in Fig. 9(a). The correction process is required to remove the earth's magnetic field, thereby improving the signal to noise ratio. Fig. 9(b) shows the corrected magnetic-field signal. Mainly, the earth's magnetic field is generated by the molten iron's flow of the outer core by a self-exciting dynamo process. It varies from 20 to 80 μT with geographic coordinate and with frequency below 1 Hz [12, 23]. Therefore, the transmitted magnetic-field signal can be separated from the total received magnetic-field signal using low noise amplifier and band pass filter.

Finally, semiconductor based contact-less and spark-less switch is necessary to avoid the potential explosion of flammable coal-bed methane (CBM) and coal dust for safe operation of the FMFG.

4. Conclusion

The miniature pulsed ferrite magnetic field generator (FMFG) was designed for the emergency TTE communication system in mines up to 1000 m depth. Two kinds of carrier sources including electromagnetic wave and pulsed magnetic field were investigated for TTE communication. It was found that the magnetic field was about 60 dB less attenuated than 1 kHz electromagnetic wave at the same depth. Therefore, the magnetic field was suitable for TTE communication signal source. The optimized FMFG can transmit 1×10^{-10} Tesla of magnetic field up to 1000 m depth with 1 A and 1 V input. This magnetic field can be detected by flux gate or magnetic tunneling junction sensor. The diameter of FMFG was one hundred times smaller than that of AMFG to transmit the same magnetic field at a given depth. Therefore, the designed miniature FMFG TTE system can replace the conventional electromagnetic wave carrier type TTE communication system.

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