Realization of a broadband terahertz wavelength-selective coupling based on five-core fibers*

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We propose a novel kind of wavelength-selective coupling for the terahertz range based on solid five-core fiber (FCF). The performances of coupling, propagation characteristics, and confinement loss properties are numerically investigated by using a full vector beam propagation method (BPM). Simulation results show that it is possible to realize a broadband wavelength-selective coupling. The coupling length can reach 1.913 cm, and the confinement loss is better than 1.965×10^{-4} cm^{-1}. Furthermore, a parameter, the power difference, is defined, and it numerically demonstrates the working performance of the wavelength-selective coupler; that is, when the power difference is better than −15 dB, the frequency located in the range of 0.76 THz–1.00 THz is separated relatively well from the frequency of 0.3 THz. Finally, the effect of the structural parameter on the working performance of the coupler is also investigated. We show that the performance optimization is possible by appropriately tuning the core diameter, and the tunabilities of frequency and bandwidth are possible by appropriately tuning the pitch. The wavelength-selective coupler is of potential application for optical fiber sensing and communication in terahertz wavelength division multiplexer fields.

Keywords: terahertz, terahertz waveguides, coupling, multi-core fiber

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1. Introduction

Recently, studies of relevant terahertz (THz) technology have received much attention, because they have a large potential application in fields such as imaging, detection, security, and communications,[1–11] while it is essential to investigate waveguides for THz radiation,[12–18] since THz waveguides can effectively overcome the difficulty that THz systems utilizing free-space propagation suffer a large loss of energy. With increasing quality of the waveguides, an essential THz functional waveguide device has been extensively investigated in recent years.[19–23] Nielsen *et al*. reported a broadband terahertz directional coupler based on a dual-core photonic crystal fiber (PCF) with subwavelength downdoped microstructure cores.[19] Chen *et al*. also demonstrated a broadband directional coupler, but it is based on three-core PCF.[20] Bai *et al*.[21] and Jiang *et al*.[22] separately analyzed a twin-core bandgap fiber coupler at terahertz frequencies. Li *et al*. proposed a THz polarization splitter based on orthogonal microstructure dual-core PCF.[23] In summary, to date, most of the THz functional devices reported involve several THz PCF-based directional couplers and a polarization splitter, and most of them are not easy to fabricate, while as a basic component in wavelength division multiplexing optical fiber communication, little significant work has been done on achieving the THz wavelength-selective fiber device.[24] To diversify the THz functional devices and reduce the difficulty in fabrication, a THz wavelength-selective coupling employing multi-core fiber is considered.

In this paper, a new kind of broadband THz wavelength-selective coupling is proposed and demonstrated. Unlike the previously reported subwavelength micro-structured core and air-core periodic THz waveguide devices, the proposed THz waveguide device is comprised of simple solid five-core. By using the BPM, the performances of coupling, propagation characteristics, and confinement loss properties of the THz waveguide device are investigated in detail.

2. Geometric modeling

The transverse section of the novel THz wavelength-selective coupling is illustrated in Fig. 1. As depicted in this figure, the proposed wavelength-selective coupler is of a simple configuration with a core in the center surrounded by four symmetric cores, and we call these respectively the central core and outer core here. We assume that two different polymers are utilized as the core and background materials. They are TOPAS (represented by the dark gray area) and Teflon (represented by the light gray area), respectively, which have relatively low material absorption losses compared with PMMA and PC, and the refractive indices of cores and background are assumed to be 1.53 and 1.43, respectively.[23,25] The THz beam transmission thus is achieved by the high reflections resulting from these multi-core structures. The pro-

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posed fiber has the same core diameter $d = 1.2$ mm, and a pitch $\Lambda = 1.4$ mm.

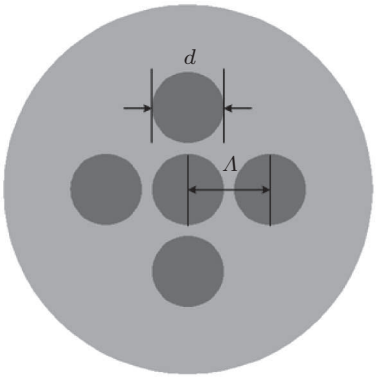


Fig. 1. Transverse section of the proposed THz wavelength-selective coupler with an FCF structure.

3. Results and discussion

By using the BPM, performances of coupling, propagation characteristics, and confinement loss properties for the proposed coupler have been numerically investigated. Figure 2 shows the variations of output normalized power with propagation distance at different operational frequencies for the central core and outer core. The THz Gaussian beam is inputted into the central core. Because the output powers of the four cores surrounding the central core are almost identical, for simplicity, the output power of only one outer core is considered here. At a frequency of 0.30 THz, as shown in Fig. 2(a), the output power decreases significantly with increasing propagation distance, and the minimum power is achieved at a propagation distance of 1.913 cm. However, the output power in a frequency range of 0.75 THz–1.00 THz is limited relatively well in the central core, and we can see that a decreasing trend of output normalized power is achieved for frequency from 0.75 THz to 1.00 THz. We think that the reason is that the Gaussian beam fluctuation increases with increasing frequency, which is contrary to the scenario shown in Fig. 2(b); we can clearly see that the output power of the outer core almost approaches zero in the frequency range of 0.75 THz–1.00 THz, and a decreasing trend of output power is also achieved for frequency from 0.75 THz to 1.00 THz, which is probably due to the fact that the output power in the central core leaks partially into the background material. For the output power of the outer core at a frequency of 0.30 THz, we can see that it increases gradually with increasing propagation distance, and its value tends to be one-fourth of the total power at a propagation distance of 1.913 cm. As for the frequency $f = 0.45$ THz located in a frequency range of 0.30 THz–0.75 THz, when the propagation distance is 1.913 cm, it can be seen that both relatively abundant energy transfers occur both in the central core and in outer cores simultaneously. Although the energy is limited relatively well in the central core at $f = 0.6$ THz located in the same frequency range, it becomes higher in the outer core, which results in weakened wavelength-selective capability of the coupler. Consequently, when the propagation distance is equal to 1.913 cm, the transmitted THz pulse through this FCF is coupled relatively well into the outer cores at the frequency of 0.30 THz; meanwhile, the output power is limited relatively well in the central cores for the frequency range from 0.75 THz to 1.00 THz. Therefore, this FCF can realize wavelength-selective coupling.

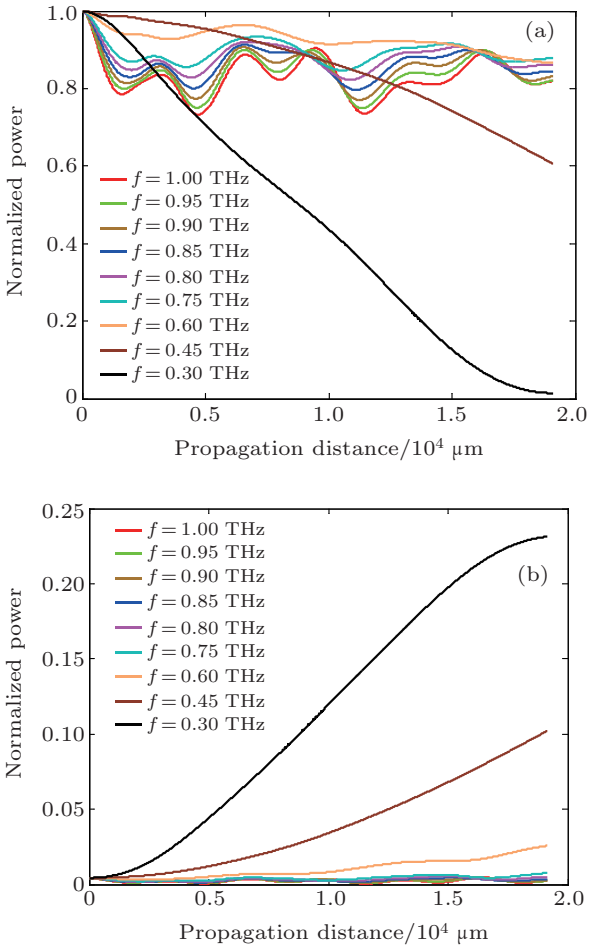


Fig. 2. (color online) Variations of normalized power with propagation distance at different operational frequencies for (a) central core and (b) outer core.

In order to observe more intuitively, we present planar figures describing the light propagation and coupling. Consequently, the mode field intensity distributions of the proposed coupler at a propagation distance of 1.913 cm for different frequencies, i.e. $f = 0.30$, 0.45, 0.60, 0.75, 0.90, and 1.00 THz are shown in Fig. 3. From Fig. 3(a), it can be clearly seen that the initially transmitted light power in the central core is coupled into the outer four cores at the frequency of 0.30 THz for the propagation distance of 1.913 cm. For Figs. 3(b) and

3(c), apart from modal field patterns of the central core, the modal field patterns of the four outer cores also have relatively high intensities. Comparatively, from Figs. 3(d)–3(f), we can observe that the predominant power of light transmits through the central core; only a small part of it couples into the outer cores. Meanwhile, with increasing frequency, powers coupled into the outer cores decrease in the frequency range from 0.75 THz to 1.00 THz. In addition, it is worth mentioning that, compared with Fig. 3(d), figure 3(f) shows that when the frequency is equal to 1.00 THz, the power leakage to a certain extent occurs in the background between the central core and the outer four cores; the power coupled into the outer cores consequently decreases, and the power variations are inversely proportional to frequency.

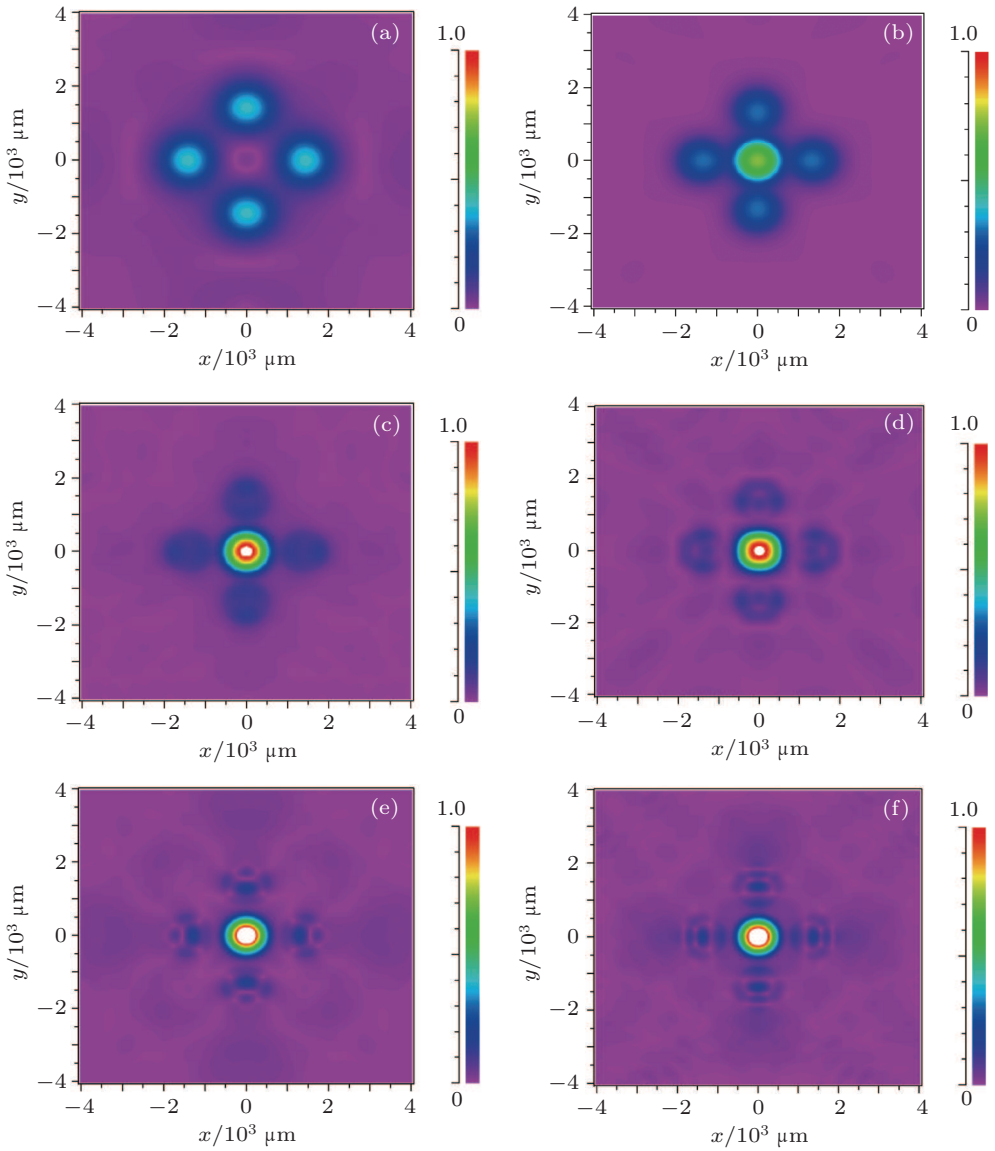


Fig. 3. (color online) Intensity distributions of the proposed coupler at a propagation distance of 1.913 cm for (a) $f = 0.30$ THz, (b) $f = 0.45$ THz, (c) $f = 0.60$ THz, (d) $f = 0.75$ THz, (e) $f = 0.90$ THz, and (f) $f = 1.00$ THz.

As for the loss characteristics of the proposed coupler, it has been known that the bulk material absorption losses of TOPAS and Teflon (cores and background material) are better than 0.25 cm^{-1} and 0.90 cm^{-1} respectively, for frequency less than or equal to 1.00 THz.[25] In this paper, for smaller coupling length, the lower transmission losses caused by the absorption losses are maintained. Another important parameter during transmission through the fiber, the confinement loss is also worthwhile to investigate, and it is expressed as

$$L_{\mathrm{c}} = \frac{20}{\ln 10} k_0 \,\mathrm{Im}(n_{\mathrm{eff}}), \tag{1}$$

where k_0 is the wave number in free space and n_{eff} is the effective refractive index. Figure 4 shows the confinement loss of the proposed coupler as a function of operational fre-

quency. It can be seen that the estimated confinement loss of 1.965×10^{-4} cm^{-1} can be reached at the frequency of 0.30 THz, while the confinement losses tend to zero in the frequency from 0.40 THz to 1.00 THz. Our simulation also indicates that a single low-index dielectric layer can achieve a good THz mode confinement with no need for multiple-layered periodic structures.

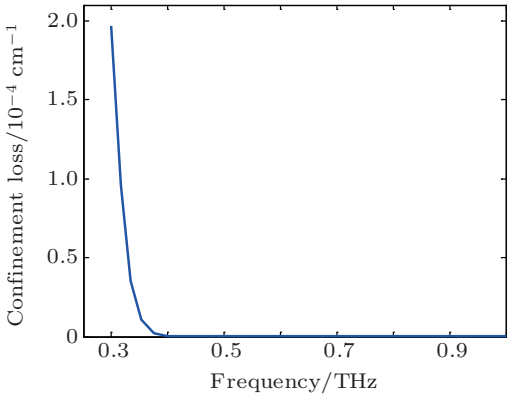


Fig. 4. (color online) Confinement loss of the proposed coupler as a function of operational frequency.

To further make clear the quantitative aspects of the above analysis, we define a parameter of the difference between the output power at a specific frequency and the output power at an arbitrary frequency within the operational frequency, and call it the power difference (PD). For the central core and outer core, their power differences are given, respectively, as follows:

$$\mathrm{PD_C} = 10\log_{10}\frac{P^{\mathrm{f}}_{\mathrm{out,c}}}{P^{\mathrm{f_i}}_{\mathrm{out,c}}}, \tag{2}$$

$$\mathrm{PD_O} = 10\log_{10}\frac{P^{\mathrm{f_i}}_{\mathrm{out,o}}}{P^{\mathrm{f}}_{\mathrm{out,o}}}, \tag{3}$$

where $\mathrm{PD_C}$ and $\mathrm{PD_O}$ are power differences of the central core and outer core, respectively. Under the above study results, the values of $P^{\mathrm{f}}_{\mathrm{out,c}}$ and $P^{\mathrm{f}}_{\mathrm{out,o}}$ are assumed to equal the output powers of the central core and outer core when the frequency $f = 0.30$ THz, and the values of $P^{\mathrm{f_i}}_{\mathrm{out,c}}$ and $P^{\mathrm{f_i}}_{\mathrm{out,o}}$ are the arbitrary output powers of the central core and outer core according to the frequency range from 0.30 THz to 1.00 THz, respectively. Figure 5 shows the variations of power difference of the central core and outer core for the proposed coupler with operational frequency.

Here, the bandwidth of the wavelength-selective coupling is defined as the frequency range within which the power difference is better than -15 dB, the effects of which for the central core and the outer core should be achieved simultaneously. From the figure, we can see that the bandwidth of -15 dB is almost 0.24 THz from 0.76 THz to 1.00 THz, and the estimated power difference of -17.78 dB is obtained at the frequency of 0.83 THz when the power difference is identical between the central core and the outer core. It is a relatively moderate frequency.

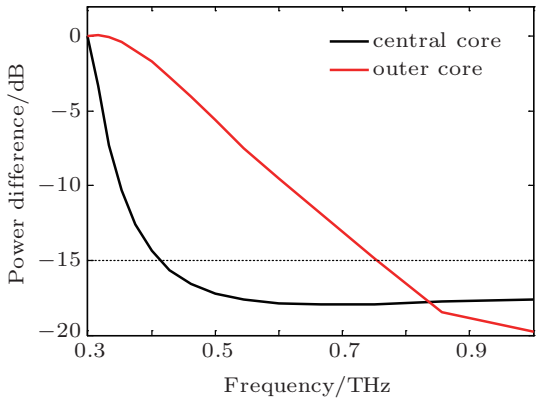


Fig. 5. (color online) Power differences of the central core and outer core for the proposed coupler versus operational frequency.

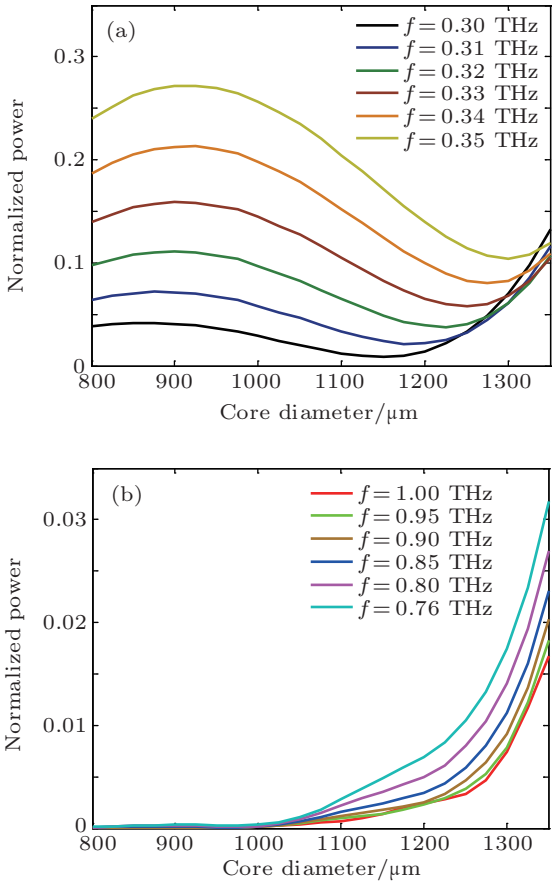


Fig. 6. (color online) Dependences of normalized power on the core diameter for (a) central core at lower frequencies and (b) outer core at higher frequencies.

The variations of structural parameters of the THz fiber can affect the working performances of the wavelength-selective coupler. According to the above discussion, we can attain that the THz pulses propagate predominantly in the outer cores at a low frequency (about 0.3 THz), while at high frequencies (about 0.76 THz–1.00 THz), the THz pulses propagate predominantly in the central core. Therefore, in what

follows, we only examine how the structural parameters influence power transmissions in the central core at low frequencies, and in the outer cores at high frequencies, where the lower the corresponding output power is, the better the performance of the coupler is. In view of these factors, when the pitch $\Lambda = 1.4$ mm and propagation distance $z = 1.913$ cm are fixed, for the central and outer cores, the dependences of normalized power on core diameter d at different frequencies are shown in Figs. 6(a) and 6(b), respectively. It can be observed that the minima of the power shift toward large core diameter when the frequency increases as shown in Fig. 6(a), and its minima show an increasing tendency to larger frequency. Specifically, as $f = 0.30$ THz, the core diameter that makes the output power minimum is a value of 1.15 mm, which indicates that for the fixed propagation distance of 1.913 cm it can present smaller output power than that of the core diameter $d = 1.2$ mm in the central core. From Fig. 6(b), when the core diameter is less than 1.00 mm, the output power tends to zero for the frequency from 0.76 THz to 1.00 THz in the outer core, and the output power shows an increasing tendency toward a larger core diameter. For a specific wavelength, the output power becomes larger with decreasing frequency. Through the above analysis, for fixed pitch and propagation distance, appropriate decrease of the core diameter can optimize the performance of the coupler, e.g. $d = 1.15$ mm.

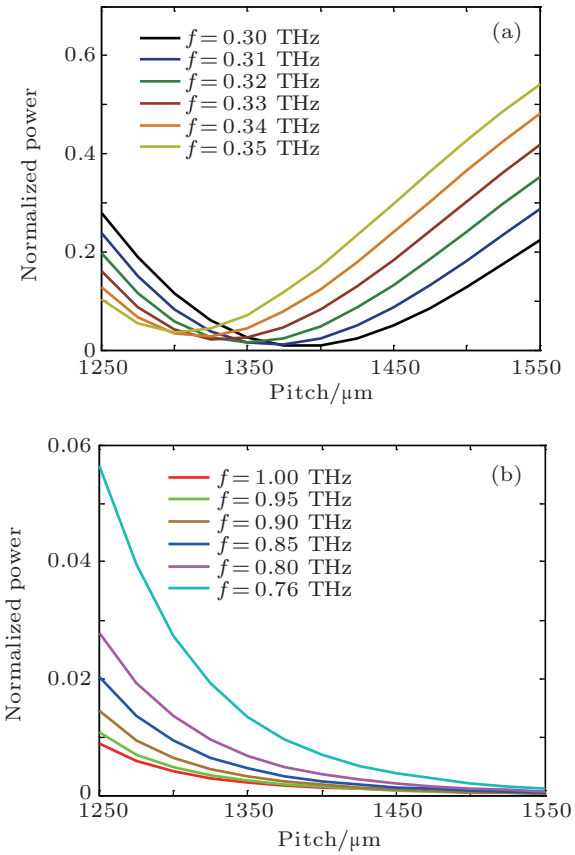


Fig. 7. (color online) Dependences of the normalized power on pitch for (a) central core at lower frequencies and (b) outer core at higher frequencies.

With the core diameter $d = 1.2$ mm and propagation distance $z = 1.913$ cm, figures 7(a) and 7(b) show the dependences of the normalized power on pitch Λ at different frequencies for the central and outer cores, respectively. From Fig. 7(a), it can be seen that the minima of the power shift toward small pitch and increase slightly with increasing frequency. Meanwhile, from Fig. 7(b), we can find that the output power increases with decreasing pitch in the outer core. Taking into account the two figures simultaneously as shown below, the wavelength-selective coupling in another frequency range can be realized by reducing the pitch appropriately, but the coupling bandwidth becomes narrow accordingly; e.g., with the pitch $\Lambda = 1.325$ mm, the frequency of 0.33 THz can be separated relatively well from the frequency range from 0.85 THz to 1.00 THz.

4. Conclusion

In this paper we have proposed and numerically demonstrated a new kind of broadband wavelength-selective fiber coupling based on a solid five-core structure. By employing the BPM, the performances of coupling, propagation properties, and the confinement loss properties of the proposed coupler are fully investigated. Results show that the proposed coupler can achieve easily a broadband wavelength-selective coupling. The coupling length can be as low as 1.913 cm. At a frequency of 0.30 THz, most of the output power is transmitted through the central core, while most of the output power is transmitted through the outer cores in a frequency range from 0.75 THz to 1.00 THz. Moreover, confinement losses are better than 1.965×10^{-4} cm^{-1}. Furthermore, the introduced power differences numerically demonstrate that the frequency located in the range 0.76 THz–1.00 THz can be separated relatively well from the frequency of 0.30 THz when the power differences of the central core and outer core are better than -15 dB simultaneously. Finally, the dependence of working performance on structural parameters is also investigated. This shows that the appropriate tuning of the core diameter can optimize the performance of the coupler, and the appropriate tuning of the pitch can adjust frequency and bandwidth.

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