We present multifrequency simultaneous VLBA observations at 15, 22, and 43 GHz toward the nucleus of the nearby radio galaxy NGC 1052. These three continuum images reveal a double-sided jet structure whose relative intensity ratios imply that the jet axis is oriented close to the sky plane. The steeply rising spectra at 15–43 GHz at the inner edges of the jets strongly suggest that synchrotron emission is absorbed by foreground thermal plasma. We detected H$_2$O maser emission in the velocity range of 1550–1850 km s$^{-1}$, which is redshifted by 50–350 km s$^{-1}$ with respect to the systemic velocity of NGC 1052. The redshifted maser gas appears projected against both sides of the jet, in the same manner as the H$_i$ seen in absorption. The H$_2$O maser gas is located where the free-free absorption opacity is large. This probably implies that the masers in NGC 1052 are associated with a circumnuclear torus or disk as in the nucleus of NGC 4258. Such circumnuclear structure could be the source of accretion onto the central engine.

Subject headings: galaxies: active — galaxies: individual (NGC 1052) — galaxies: nuclei — galaxies: Seyfert — masers

1. INTRODUCTION

NGC 1052 is a nearby ($z = 0.0049$; Knapp et al. 1978) radio galaxy whose nuclear activity is classified as low-ionization nuclear emission-line region (LINER; e.g., Gabel et al. 2000). This galaxy hosts a well-defined double-sided radio jet elongated by several parsecs with a P.A. $\sim 65^\circ$. The jet emanates from the nucleus and can be traced out to kiloparsec scales (Cohen et al. 1971; Wrobel 1984; Jones 1984; Kellermann et al. 1998; Kameno et al. 2001; Vermeulen et al. 2003; Kadler et al. 2004b). Radio observations of the low-luminosity active galactic nucleus (AGN) of NGC 1052 with very long baseline interferometry (VLBI) at multiple frequencies have revealed the presence of a dense circumnuclear structure, which obscures the very center of this elliptical galaxy (Kellermann et al. 1998; Kameno et al. 2001; Vermeulen et al. 2003; Kadler et al. 2004b). Proper motion between the two sides of the jet and structural evolution has been detected in this galaxy. VLBI observations showed that the proper motion between the two sides of the jet had an apparent velocity of $(0.26 \pm 0.04)c$ from 1995 to 2001 (e.g., Kellermann et al. 1998; Vermeulen et al. 2003). A gap between the eastern and western jets, where the nucleus is supposed to be, can be seen until 1999 (Claussen et al. 1998; Kellermann et al. 1998; Vermeulen et al. 2003). In 2000, however, a nuclear component appeared between the eastern and western jets (Kameno et al. 2001). These authors found a central condensation of the plasma which covers about 0.1 and 0.7 pc of the approaching and receding jets, respectively. They proposed a parsec-scale circumnuclear torus model for NGC 1052. X-ray spectra also imply a high column density of $10^{22} - 10^{23}$ cm$^{-2}$ toward the center, and support the presence of a dense gas torus (Guainazzi & Antonelli 1999; Weaver et al. 1999; Kadler et al. 2004a).

The center of NGC 1052 harbors a luminous H$_2$O megamaser, which is redshifted by 50–350 km s$^{-1}$ with respect to the systemic velocity of the galaxy (1491 km s$^{-1}$; de Vaucouleurs et al. 1991). The spectral profile typically shows a broad velocity width of $\sim 100$ km s$^{-1}$ (FWHM; Bratza et al. 1994, 1996, 2003). Past VLBI images reveal that H$_2$O maser gas with a velocity range of 1585–1685 km s$^{-1}$ is distributed along the western jet, 0.05–0.1 pc shifted to the west from the gap between the double-sided jets in 1995 November. Excitation by shocks into the dense molecular clump which lies in or around the radio jet, or amplification of the radio continuum emission of the jet by foreground molecular clouds, was suggested by Claussen et al. (1998). On the other hand, Kameno et al. (2005) presented the circumnuclear torus model to explain the time variability of the H$_2$O maser emission. Relevant to the interpretation of the H$_2$O maser emission line, several other absorption lines are also found toward the center of NGC 1052 (H$_i$ for van Gorkom et al. 1986; OH for Omar et al. 2002; HCO$^+$, HCN, and CO for Liszt & Lucas 2004).

In order to confirm the positional relation between the H$_2$O maser gas and the proposed circumnuclear torus, we observed the continuum and maser emissions in the nucleus of NGC 1052 with the Very Large Baseline Array (VLBA). We adopt $z = 0.0049$ (Knapp et al. 1978), which corresponds to a distance $D = 20$ Mpc to NGC 1052 assuming $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$. Hence 1 mas corresponds to 0.095 pc.

2. OBSERVATIONS AND DATA REDUCTION

The observations toward NGC 1052 were carried out at 15, 22, and 43 GHz on 2000 July 24 with all 10 antennas of the VLBA. On source times of NGC 1052 at 15, 22, and 43 GHz were 170, 190, and 130 minutes, respectively. We observed 3C454.3 and 3C84 for phase calibrations and bandpass calibrations.

The data were recorded in left circular polarization over four 8 MHz intermediate frequency (IF) channels, and were divided into 256 spectral channels for each IF channel. The continuum emissions were measured with all four IF channels at 15 and 43 GHz. At 22 GHz, the LSR velocities of 1000, 1200, 1650, and 1750 km s$^{-1}$ were each centered on one of the IF channels. The
two IF channels centered on 1650 and 1750 km s\(^{-1}\), covered the velocity range from 1560 to 1840 km s\(^{-1}\), where the H\(_2\)O maser emissions have been detected. The other two IF channels were used to observe the line-free continuum emission. The correlation process was done using the NRAO VLBA correlator.

Data reduction including calibration, data flagging, fringe fitting, and imaging utilized using the NRAO AIPS package. 3C 454.3 and 3C 84 were used as clock-offset and bandpass calibrators. All spectral channels at 15 and 43 GHz and the line-free spectral channels at 22 GHz were integrated into a single continuum channel for each band. Fringe fitting was conducted using the single continuum channel for each band. The hybrid imaging process, which involved iterative imaging with CLEAN and self-calibration, was done at all frequency bands. At 22 GHz, the solutions of fringe fitting and self-calibration obtained from the 22 GHz continuum channel were applied to line channels of H\(_2\)O maser emission.

The overlapping channels of the two IFs with the H\(_2\)O maser line were removed and the two IFs were joined together using the AIPS task uvglu. Channel maps of H\(_2\)O maser emission were made every 6.74 km s\(^{-1}\), averaging every 10 spectral channels. The continuum emission of the line channels were subtracted from the each spectral channel map in the AIPS task uvsu. The relative positional accuracy of a maser spot ranged over 0.02–0.18 mas, depending on the signal-to-noise ratio and the spatial structure of the spot. The synthesized beam size and rms level for the 15, 22, and 43 GHz images are given in Table 1.

### Table 1

| \(\nu\) (GHz) | Major Axis (mas) | Minor Axis (mas) | P.A. (deg) | rms Level (mJy beam\(^{-1}\)) |
|--------------|-----------------|-----------------|-----------|-----------------------------|
| 15.\(a\)     | 1.30            | 0.49            | -4.8      | 0.24                        |
| 22\(a\)      | 0.86            | 0.32            | -7.1      | 1.07                        |
| 22\(b\)      | 22\(b\)         | 0.32            | -7.1      | 5.66                        |
| 43\(a\)      | 0.39            | 0.17            | -2.8      | 1.45                        |

\(a\) Continuum map.

\(b\) Channel map of H\(_2\)O maser. Velocity resolution is 6.74 km s\(^{-1}\).

images with a 1.30 \(\times\) 0.49 mas beam at 15, 22, and 43 GHz, where \(k\) and \(\nu\) are the knot ID (B, C1, C2) and a frequency, respectively. Then we derived relative offsets \((\delta x^k, \delta y^k)\) to minimize the positional residuals \(\chi^2\), defined as

\[
\chi^2 = \sum_k \left[ \frac{(x^k - \delta x^\nu - x_0^\nu)^2}{\sigma_x^2 + \sigma_{x_0}^2} + \left( \frac{y^k - \delta y^\nu - y_0^\nu)^2}{\sigma_y^2 + \sigma_{y_0}^2} \right) \right],
\]

where \(\sigma_x^2\) and \(\sigma_y^2\) are standard positional errors of knot \(k\) at frequency \(\nu\) from the Gaussian fitting, and \(x_0^\nu\) and \(y_0^\nu\) are the frequency of the reference image (e.g., Kameno et al. 2001). We choose 22 GHz as the reference frequency \(\nu_0\). Finally, we could overlay the images at 15 GHz and 43 GHz with the image at 22 GHz, with positional errors of \((\pm 0.05, \pm 0.04)\) mas and \((\pm 0.05, \pm 0.09)\) mas, in R.A. and declination, respectively.

3.2. Free-Free Absorption Opacity Distribution

After restoring with the same beam size (1.30 \(\times\) 0.49 mas), we obtained spectral index images using the restoring images in the AIPS task comb (Fig. 2). Pixels with intensities less than the 3 \(\sigma\) level in all the restored images are clipped. The spectral index images indicate that most parts of the two-sided jet structure have optically thin synchrotron spectra at 15–43 GHz except at the inner edge; a steeply rising spectrum (\(\alpha_{22} = 3.2 \pm 0.1, \alpha_{43} = 3.1 \pm 0.1; S \propto \nu\)) at the western edge of knot B and at the eastern edge of knot C3 is revealed. The spectral index exceeds the theoretical limit for synchrotron self-absorption (\(\alpha = 2.5\)). The highly rising spectrum of the inner edge of the jets implies that the synchrotron emission is obscured through the free-free absorption (FFA) by the foreground dense plasma, which is consistent with past multi-frequency observations (Kameno et al. 2001; Vermeulen et al. 2003; Kadler et al. 2004b).
We fitted the continuum spectrum at 15–43 GHz to the FFA model,

\[ S_\nu = S_0 \nu^\alpha \exp(-\tau_0 \nu^{-2.1}), \]

where \( S_0 \) is the flux density in Jy at a frequency of 1 GHz extrapolated from the spectrum, and \( \tau_0 \) is the FFA opacity at 1 GHz (Kameno et al. 2000). Obtained FFA opacity images along the jet axis (P.A. = 65°) reveal that high opacity (\( \tau_0 \sim 1000 \)) is found in the inner edge (Fig. 3). The fit in the inner edge has larger errors, because the continuum spectrum of the inner edge does not show the peak between 15 and 43 GHz. The space distribution of \( \tau_0 \) implies that the dense cold plasma covers \( \sim 1 \) mas (0.1 pc), which is equal to the restoring beam size, in the inner edge of the jets, where the central engine is supposed to exist.

### 3.3. H$_2$O Maser Emission

In our observations, significant H$_2$O maser emission within the velocity range of 1550–1850 km s$^{-1}$ were detected, 50–350 km s$^{-1}$ redshifted from the systemic velocity of the galaxy. This is consistent with past single-dish observations (Braatz et al. 1994, 1996, 2003; Kameno et al. 2005). Figure 4 shows the radio continuum image at 22 GHz and the distribution of H$_2$O maser spots of our observations (2000 July). The maser spots consist of two clusters; the eastern cluster and the western cluster are located on knots B and C3, respectively. The H$_2$O masers projected on the approaching jet or on the eastern cluster were detected for the first time. The velocity range is 1550–1850 km s$^{-1}$, which is same as the whole velocity width of the H$_2$O maser spectral profile. The maser spots in the eastern cluster with a velocity of 1550–1700 km s$^{-1}$ are distributed within 1 mas (0.1 pc) of knot B. The maser spots with a velocity of 1700–1850 km s$^{-1}$ are more tightly concentrated within 0.2 mas (0.02 pc) of the peak of knot B. On the other hand, the western cluster is detected with a velocity range of 1550–1750 km s$^{-1}$. These maser spots are distributed along the jet axis that span \( \sim 1 \) mas (0.1 pc), and show some velocity shift along the direction. Position-velocity diagrams of the H$_2$O maser spots along the jet axis (Fig. 5) also reveal the trend of a velocity gradient of \( \sim 250 \) km s$^{-1}$/mas$^{-1}$ in the western cluster. We note that Claussen et al. (1998) showed a velocity gradient along the east-west direction (\( \sim 100 \) km s$^{-1}$/mas$^{-1}$) in the maser cluster on the western jet knot. A velocity gradient in the eastern cluster is not obvious (Fig. 5a).

The peak flux density for each maser spot and the continuum emission at 22 GHz along the jet axis are shown in Figure 6. The H$_2$O maser flux and the continuum flux do not appear to be correlated. The brighter maser spots in the western cluster are located closer to the gap between B and C3. This trend is also seen in the plot of the flux density of H$_2$O maser spots vs. their right ascension offset in Claussen et al. (1998). In Figure 6, the central engine may be located around 1 mas in relative right ascension if the FFA opacity peak is a good indicator.

### 4. DISCUSSION

#### 4.1. Orientation of the Jet Axis

The brightness temperature ratio between the approaching and receding jets is related to the viewing angle of the jet axis and the true jet speed. Assuming that knots A and C1 form a symmetric pair of knots on either side of the nucleus, their intensity ratio \( R \) is given by

\[ R = \frac{S_A \phi_{maj}^A \phi_{min}^A}{S_C \phi_{maj}^C \phi_{min}^C} = \left( \frac{1 + \beta \cos \theta}{1 - \beta \cos \theta} \right)^{3-\alpha}, \]

where \( S_A \) and \( S_C \) are the flux density of knots A and C1, respectively, \( \phi_{maj}^A, \phi_{min}^A, \phi_{maj}^C, \phi_{min}^C \) are the FWHM sizes of the knots A and C1, \( \beta \) is the true jet velocity as a fraction of the speed of light \( (c) \), \( \theta \) is the viewing angle, \( \alpha \) is the spectral index. Since the knots A and C1 are shifted 5 mas from the center, the effect of FFA on A and C1 would be small. Adopting \( \beta = 0.64 \) (Kadler et al. 2004b) and \( \alpha = -1 \), the viewing angle is estimated to be 79°–80° and 76°–90° using the flux density at 15 and 22 GHz, respectively. Therefore, the jet axis is considered to be nearly parallel to the sky plane. The estimated minimum angles are larger than those obtained by Kameno et al. (2001) and Vermeulen et al. (2003). In their data, the receding component was located closer to the center, and the emission of
Fig. 2.—Spectral index images of (a) 15–22 GHz, and (b) 22–43 GHz. Both images were restored with the same beam size, 1.30 × 0.49 mas, as shown in the lower left corner. The interval of contour levels is 1, and the dashed lines indicate negative.
Fig. 3.—(a) Free-free absorption opacity along the jet axis (P.A. = 65°). (b) Two-dimensional distribution of free-free absorption opacity. All images at 15, 22, and 43 GHz are restored with the same beam size, 1.30 × 0.49 mas. The white line indicates the direction of the slice cut.
Fig. 4.—(a) Doppler velocity distribution (colored filled circles) of H$_2$O maser spots in NGC 1052. (b) Relative distributions of H$_2$O maser spots (filled circles) with respect to the continuum image at 22 GHz (contours).
the receding component could be absorbed more due to the effect of FFA. The obtained intensities of the jets could be more asymmetric than the intrinsic intensities, and the asymmetric intensity ratio leads to the estimation of the inclined jet axis.

4.2. Interpretation of H$_2$O Maser

There are two main ideas about what the H$_2$O masers of NGC 1052 are associated with, the jet or the circumnuclear torus (Claussen et al. 1998; Kameno et al. 2005). Here we discuss the plausible nuclear structure in NGC 1052 to account for these observed characteristics: (1) FFA plasma spanning $\sim$1 pc; (2) redshifted velocity of the H$_2$O masers with respect to the systemic velocity of NGC 1052; (3) H$_2$O masers that appear to be projected against knots B and C3; (4) a velocity gradient of the H$_2$O masers along the jet; and (5) more dominant FFA opacity and H$_2$O maser emission on the western receding jet as compared to the eastern approaching jet.

One possible scenario is that the H$_2$O masers are associated with a circumnuclear torus, as illustrated in Figure 7. The H$_2$O masers are seen where the FFA opacity is large, and this suggests that the H$_2$O masers and the plasma exist close to each other. In the case of the H$_2$O megamaser emission in NGC 4258, Neufeld & Maloney (1995) and Herrnstein et al. (1996) proposed that the molecular disk consists of several layers, including a heated molecular layer where the H$_2$O masers reside. Kameno et al. (2005) applied this idea to the circumnuclear torus model in NGC 1052. A hot ($\sim$8000 K) plasma layer is created on the inner surface of the torus because of the direct exposure to the X-ray radiation from the central source. This layer is responsible for the free-free absorption. The X-ray dissociation region (XDR) which lies immediately next to the plasma layer inside the torus is heated above $\sim$400 K because it is still partially irradiated by the X-ray radiation (Maloney 2002). Excited H$_2$O molecules in the XDR will amplify the continuum seed emission from the jet knots in the background and result in maser emissions. The presence of masers on both jets indicates the thickness of the torus along the orientation of the jet, covering at least knots B and C3. If the orientation of the jet axis is parallel to the sky plane, the thickness of the torus should therefore be at least 0.2 pc. More dominant FFA and H$_2$O masers on the receding jet support the circumnuclear torus scenario, since the path length within the torus toward the receding jet would be greater.

If the H$_2$O masers are associated with the torus, the redshifted spectrum of the H$_2$O maser emission would be accounted for by a contraction toward the central engine. The positional-velocity diagram along the jet axis (Fig. 5) makes the H$_2$O maser gas closer to the central engine appear to be more redshifted. Such a velocity shift as a function of positional offset could indicate the acceleration of the infalling gas toward the central engine. The blueshifted H$_2$O maser emission would not be detected in the model. Because H$_2$O maser emission is seen when jet knots are located behind the XDR layer in the torus, the spatial structure of H$_2$O masers could be varied as the jet knots eject and run behind the torus. The maser gain length and the radial velocity along the line of the sight would change when the jet knots run behind the torus, and it could also cause time variations in
the flux and velocity of the maser. This idea was proposed by Kameno et al. (2005) to explain the emergence of a narrow maser feature seen in 2003 at 1787 km s$^{-1}$; it could also account for the variations in maser profile shown in Braatz et al. (2003).

The outer region of the torus remains neutral in either molecular or atomic form. Possibly, H$^\text{i}$ gas could also be associated with the outer region of the circumnuclear torus. It is reasonable to suppose that infalling H$^\text{i}$ gas toward the center results in the redshifted absorption line detected on both approaching and receding jets, just as in the case for the H$_2$O maser emission. Thus, the circumnuclear torus scenario can explain the observed characteristics.

Another possible explanation is the excitation of the H$_2$O masers by the outflowing jet as Claussen et al. (1998) proposed, and as interpreted in the case of Mrk 348 (Peck et al. 2003). The jet excitation scenario is thought to have an advantage in explaining the velocity gradient along the jet axis. The western maser cluster can be then explained easily because the maser spots in the western cluster are all redshifted and appear projected against the receding jet. However, the jet excitation scenario cannot explain why the masers of the eastern cluster projected against the approaching jet also show the same redshifted spectrum. If the exact systemic velocity of the central engine is not 1490 km s$^{-1}$ but around 1700 km s$^{-1}$, the jet excitation scenario would become likely. For the masers in the western cluster moving with the most redshifted velocity ($\sim$400 km s$^{-1}$) from the systemic velocity of the galaxy, the maser gas should move $1.9 \times 10^{-3}$ pc eastward from 1995 November to 2000 July, because the jet axis is close to the sky plane. This motion is too small to detect for the five year multi-epoch observations. Further VLBI observations are necessary in order to detect the proper motion of H$_2$O maser spots in the jet excitation scenario.

5. CONCLUSIONS

We conducted multifrequency observations toward the center of NGC 1052 at 15, 22, and 43 GHz with the VLBA. Ratios of the brightness temperature of the approaching and the receding jet knots indicate that the angle of the jet axis to the line of sight is $\geq 76^\circ$, or nearly parallel to the sky plane. The aligned continuum images show steeply rising spectra spanned in the inner 0.2 pc around the nucleus, which imply FFA by dense plasma in a circumnuclear torus. H$_2$O maser emission is detected at velocities by 150–350 km s$^{-1}$ redshifted from the systemic velocity of the galaxy, which is consistent with past single-dish observations. The maser spots are projected against the inner knots of both the approaching and receding jets, where the FFA opacity is large. A clear velocity gradient along the jet axis in the western cluster is seen, but the eastern cluster does not show such a clear velocity trend. The more redshifted maser spots lie closer to the center.

Positional coincidence between the H$_2$O masers and a plasma torus suggests that the H$_2$O maser emission arises from the circumnuclear torus. If the H$_2$O masers is moving as contraction toward the center, the redshifted spectrum and the velocity gradient of the H$_2$O maser emission can be explained fairly well. Alternatively, the H$_2$O masers could be excited by the interaction between the jet and circumnuclear molecular clouds. A weak point of the jet excitation scenario is the difficulty of explaining
why the eastern cluster of H$_2$O masers projected against the approaching jet is also redshifted.

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