Journal of the Korean Astronomical Society
48: 357 ∼ 364, 2015 December

http://dx.doi.org/10.5303/JKAS.2015.48.6.357
pISSN: 1225-4614 · eISSN: 2288-890X
http://jkas.kas.org

Simultaneous Observations of H_2O and SiO Masers toward Known Extragalactic Water Maser Sources

Se-Hyung Cho, Dong-Hwan Yoon, Jaeheon Kim, Do-Young Byun, and Jan Wagner

Radio Astronomy Division, Korea Astronomy and Space Science Institute, 776 Daedukdae-ro, Yuseong-gu, Daejeon 305348, Korea; cho@kasi.re.kr, dhyoon83@kasi.re.kr, jhkim@kasi.re.kr, bdy@kasi.re.kr, jwagner@kasi.re.kr

Received November 16, 2015; accepted December 6, 2015

Abstract: We observe ten known 22 GHz H_2O maser galaxies during February 19–22, 2011 using the 21 m Tamna telescope of the Korean VLBI Network and a new wide-band digital spectrometer. Simultaneously we searched for 43 GHz SiO $v = 1$, 2, $J = 1$–0 maser emission. We detect H_2O maser emission towards five sources (M 33, NGC 1052, NGC 1068, NGC 4258, M 82), with non-detections towards the remaining sources (UGC 3193, UGC 3789, Antennae H_2O-West, M 51, NGC 6323) likely due to sensitivity. Our 22 GHz spectra are consistent with earlier findings. Our simultaneous 43 GHz SiO maser search produced non-detections, yielding – for the first time – upper limits on the 43 GHz SiO maser emission in these sources at a 3 σ sensitivity level of 0.018 K–0.033 K (0.24 Jy–0.44 Jy) in a 1.75 km s^{-1} velocity resolution. Our findings suggest that any 43 GHz SiO masers in these sources (some having starburst-associated H_2O kilomasers) must be faint compared to the 22 GHz H_2O maser emission.

Key words: galaxies: active — galaxies: nuclei — ISM: molecules — masers — radio lines: galaxies

1. Introduction

Maser emission has been detected in our Galaxy from many molecular species. The same maser lines can also occur in external galaxies, yet only few have been detected. One issue is the sensitivity of the observing facilities. External galaxies are distant compared to Galactic maser sources, and typically only kilo-, mega-, or gigamasers, labeled according to the maser luminosities relative to Galactic counterparts, can be detected.

The first extragalactic detection was that of 22 GHz H_2O maser emission toward the giant H II region IC 133 in the disk of the galaxy M 33 (Churchwell et al. 1977). After considerable improvements in sensitivity, extragalactic H_2O masers have been detected towards over 150 galaxies (see web sites of the Water Maser Cosmology Project[1] and Megamaser Cosmology Project[2]). The OH maser species is detected towards nearly 120 galaxies (Klockner et al. 2004; Impellizzeri 2008). Four new H_2O masers were added by Wagner (2013) in a study of dual-species (OH and H_2O) maser galaxies. Recently, extragalactic masers of H_2CO, CH_3OH, and SiO molecules were found, and Wang et al. (2014) report the first triple-species maser galaxy.

Masers are good probes for studying extreme physical conditions and dynamics in different regions of, e.g., nuclear starbursts, merging galaxies, outflows in active galaxies, and accretion disks around supermassive black holes in active galactic nucleis (AGNs) using very long baseline interferometry (VLBI). Water megamasers allow to determine accurate supermassive black hole masses, galaxy distances, and an accurate Hubble constant (Braatz et al. 2008; Reid et al. 2009; Kuo et al. 2011; Humphreys et al. 2013). A review of megamasers can be found in Lo (2005). See also Tarchi (2012).

With regard to SiO maser lines, which are very common in oxygen-rich, evolved stars in our Galaxy, only one extragalactic stellar SiO ($v = 1$, $J = 2$–1) maser source has been detected towards the red supergiant IRAS 04553-6825 in the LMC (van Loon et al. 1996). In 2014 the high vibrational state maser of SiO ($v = 3$, $J = 2$–1) and a CH_3OH maser were detected towards the nearby Seyfert 2 galaxy NGC 1068 using the IRAM 30 m telescope (Wang et al. 2014). Drawing upon similarities with the H_2O maser line velocities in this "AGN disk/jet maser" galaxy (cf. Gallimore et al. 2001), Wang et al. associated SiO and CH_3OH megamasers with the AGN accretion disk and a jet-cloud interaction, respectively. While such an association needs to be confirmed by imaging, it also opens the question whether SiO masers might be common in H_2O maser galaxies. The literature, however, finds no systematic searches for SiO masers in H_2O maser galaxies. Thus, while carrying out test observations with the Tamna 21 m telescope of the Korean VLBI Network (KVN) to test the performance of a new wide-band digital spectrometer, we also undertook a simultaneous search for SiO masers towards ten known H_2O maser galaxies.

In this paper, we report the results of the H_2O maser observation and SiO maser search. In Section 2, we present the source selection and observations. Observational results and a discussion including the comments on individual sources, and the operation and performance of the wide-band digital spectrometer, are given in Section 3. A summary is given in Section 4.

Corresponding author: S.-H. Cho
[1]http://www.cfa.harvard.edu/~lincoln/demo/HoME/
[2]http://safe.nrao.edu/wiki/bin/view/Main/MegamaserCosmologyProject

Table 1
Ten Known Extragalactic H_2O Maser Sources

Source	R.A. (J2000) (h:m:s)	Dec. (J2000) (d:m:s)	V_{sys} (km s^{-1})	D (Mpc)	Ref.
M 33	01 33 16.50	+30 52 50.0	−180	0.7	Huchtmeier et al. 1988
NGC 1052	02 41 04.80	−08 15 21.0	1470	20.0	Knapp et al. 1978
NGC 1068	02 42 40.70	−00 00 48.0	1137	14.4	Gallimore et al. 2001
UGC 3193	04 52 52.70	+03 03 24.0	4454	59.4	Bennert et al. 2009
UGC 3789	07 19 31.60	+59 21 21.0	3243	46	Braatz & Gugliucci 2008
M 82	09 55 52.20	+69 40 47.0	200	3.53	Kennicutt et al. 2008
Antennae (H_2O W)	12 01 53.10	−18 53 09.8	1664	22	Sanders et al. 2003
NGC 4258	12 18 57.50	+47 18 14.0	472	7.98	Freedman et al. 2001
M 51	13 29 52.70	+47 11 43.0	463	9.6	Greenhill 2002
NGC 6323	17 13 18.00	+43 46 56.0	7772	106	Kuo et al. 2011

Notes. V_{sys}: Systemic velocities of the galaxies based on the optical velocity convention, measured with respect to the LSR.

Table 2
Observation Parameters

	H_2O 6_{16}–5_{23}	SiO v=1, J=1–0	SiO v=2, J=1–0
Observed Dates		February 19–22, 2011	
Rest Frequencies (GHz)	22.235080	43.122080	42.820587
Velocity Bandwidth (km s^{-1})	3450	1780	1790
Velocity Resolution* (km s^{-1})	1.69	1.75	1.75
System Temperature (K)	91–104	136–162	147–174
Conversion Factor (Jy K^{-1})	12.08	13.29	13.29
Attained 3σ Sensitivity (K)	0.018–0.027	0.018–0.033	0.018–0.033

Notes. *After Hanning smoothing over 2 (at 22 GHz) and 4 (at 43 GHz) spectrometer channels.

2. SOURCE SELECTION AND OBSERVATIONS

Our ten observed sources are listed in Table 1. Nine sources with relatively strong H_2O maser emission were selected from a catalog of galaxies detected in H_2O maser emission[3]. The Antennae (H_2O West) galaxy was selected from Brogan et al. (2010). Columns 1, 2, and 3 of Table 1 list our source names and positions with regard to the right ascension (R. A.) and declination (Dec.). Column 4 lists the systemic velocity of the target source. The distance and its reference are given in Columns 5 and 6, respectively.

We observed the H_2O $6_{16} - 5_{23}$ (22.235080 GHz) and SiO $v = 1$, 2, $J = 1$–0 (43.122080 GHz, 42.820587 GHz) maser lines during February 19 to 22, 2011 using the KVN Tamna 21 m single-dish radio telescope on Jeju island. The KVN system has a unique quasi-optic system for observing simultaneously at four frequency bands (22, 43, 86 and 129 GHz) using three dichroic low-pass filters (Han et al. 2008, 2013). We used 22 GHz and 43 GHz band cooled HEMT (High Electron Mobility Transistor) receivers adjusted to receive only left-circular polarized signals.

Our observation parameters are presented in Table 2. The digital spectrometer was set up in wide-band mode with a bandwidth of 256 MHz, corresponding to a radial velocity coverage of approximately 3500 km s^{-1} (at 22 GHz) and 1780 km s^{-1} (at 43 GHz). The velocity resolution was 0.84 km s^{-1} and 0.43 km s^{-1} at 22 and 43 GHz, respectively, and was adjusted to approximately 1.7 km s^{-1} using Hanning smoothing. The system noise temperatures were 114 K–130 K at 22 GHz and 170 K–218 K at 43 GHz depending on the elevation and weather conditions. The half power beam widths and aperture efficiencies of the KVN Tamna telescope were measured and found to be 122″, 0.66 (at 22 GHz) and 64″, 0.60 (at 43 GHz), respectively (Lee et al. 2011). We observed in position switching mode. The pointing accuracy was checked every two hours using strong SiO maser sources located near our target sources. The on-source integration time was close to one hour.

The data were calibrated using the chopper wheel method, which corrects atmospheric attenuation and the antenna gain variations depending on the elevation, in order to determine antenna temperature T_A^*. Detection upper limits at 3σ noise levels were 0.018 K–0.027 K (0.22 Jy–0.33 Jy) at 22 GHz and 0.018 K–0.033 K (0.24 Jy–0.44 Jy) at 43 GHz. The conversion factors of the KVN Tamna telescope from antenna temperature to flux density were approximately 12.08 Jy K^{-1} at 22 GHz, and 13.29 Jy K^{-1} at 43 GHz.

3. OBSERVATIONAL RESULTS AND DISCUSSION

Simultaneously obtained spectra of the detected H_2O $6_{16} - 5_{23}$ maser lines and the non-detected SiO $v = 1$, 2, $J = 1$–0 maser lines from five sources are shown in Figure 1. We detected H_2O masers towards spiral galaxy M 33, elliptical galaxy NGC 1052, Seyfert 2 galaxies NGC 1068 and NGC 4258, and starburst galaxy M 82. The NGC 4258 disk megamasers had the strongest peak

[3] http://www.nrao.edu/~jbraatz

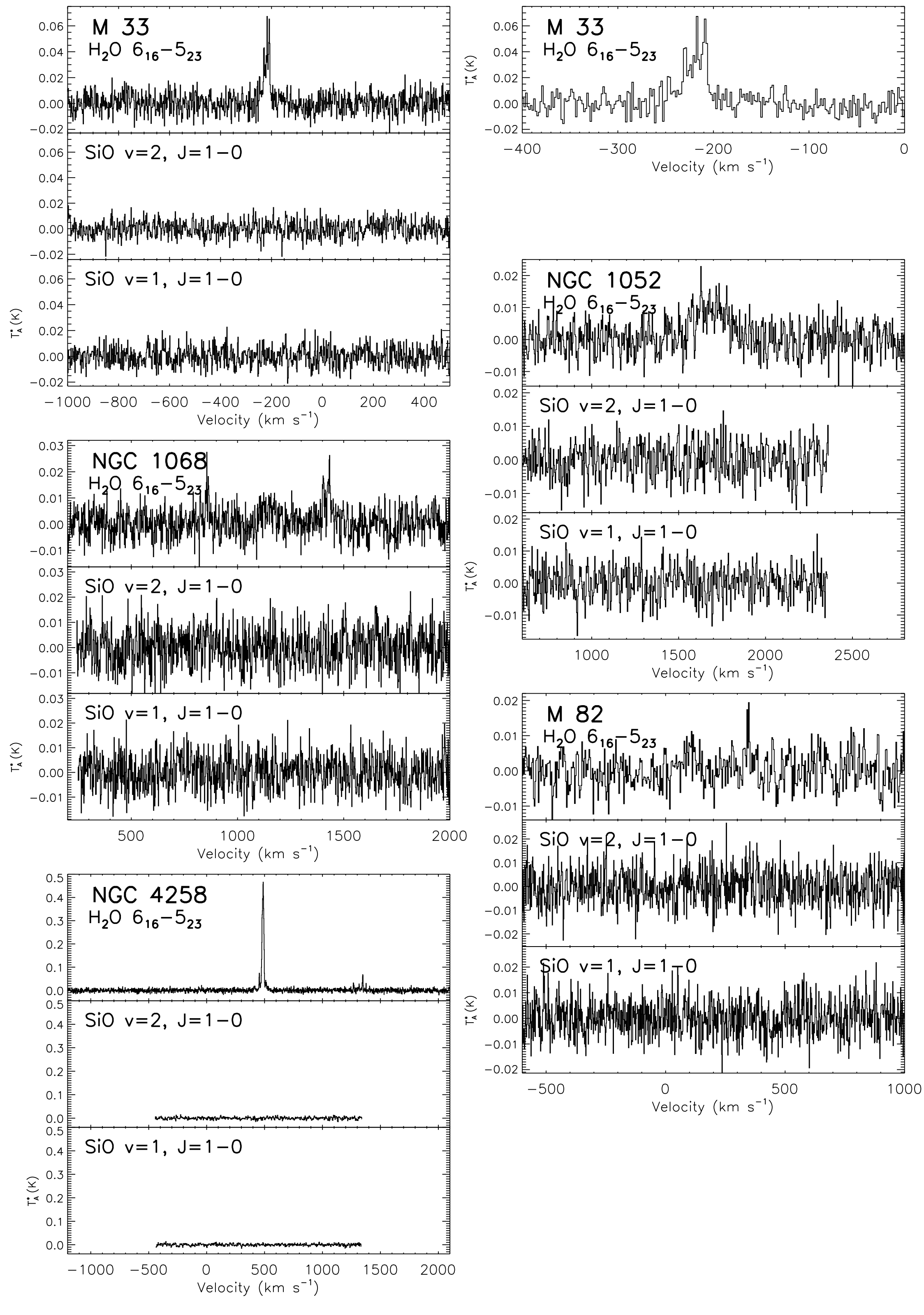

Figure 1. Simultaneously obtained spectra of detected H_2O $6_{16} - 5_{23}$ maser lines and non-detected SiO $v = 1$, 2, $J = 1$–0 maser lines from five extragalactic sources in Feb. 2011. Another M 33 H_2O maser spectrum on the right side is enlarged from $V_{\rm LSR} = -400\,{\rm km\ s^{-1}}$ to $0\,{\rm km\ s^{-1}}$.

Table 3
Results of the H_2O and SiO Maser Observations

Source	S_{peak} (K)		$\int Sdv$ (K km s^{-1})	L ($L_\odot$)	
	H_2O 6_{16}–5_{23}	SiO v=1, v=2	H_2O 6_{16}–5_{23}	H_2O 6_{16}–5_{23}	SiO v=1, v=2
M 33	0.043^C, 0.067^C, 0.065^C	< 0.022, < 0.019	1.50^C	0.21	< 0.02, < 0.02
NGC 1052	0.011^C	< 0.014, < 0.014	2.62^C	290	< 11, < 11
NGC 1068	0.028^B	< 0.019, < 0.022	0.33^B	19	< 7, < 8
	0.011^C		0.34^C	20	
	0.018^R, 0.027^R		0.67^R	38	
UGC 3193	< 0.019	< 0.022, < 0.024	···	< 54	< 139, < 154
UGC 3789	< 0.019	< 0.022, < 0.024	···	< 32	< 84, < 92
M 82	0.011^B	< 0.019, < 0.022	0.36^B	1.2	< 0.4, < 0.5
	0.019^R		0.25^R	0.9	
Antenna (H_2O W)	< 0.022	< 0.024, < 0.026	···	< 9	< 21, < 24
NGC 4258	0.074^C, 0.47^C	< 0.014, < 0.014	9.76^C	172	< 2, < 2
	0.032^R, 0.028^R, 0.069^R, 0.020^R		0.98^R	17	
M 51	< 0.019	< 0.019, < 0.019	···	< 1.4	< 3.3, < 3.3
NGC 6323	< 0.019	< 0.022, < 0.026	···	< 169	< 438, < 532

Notes. ^{B} indicates Blue–shifted maser features, ^{C} Central maser features, and ^{R} Red-shifted maser features. Upper limits are 3σ.

and showed a broad range of emission, although blue components were not detected at this epoch.

The spectral features towards these maser sources are consistent with earlier detections, and exhibit the characteristic spectral properties that reflect the different maser origins in these galaxies (e.g., masing Keplerian accretion disk, jet-related masers, star-forming activity). As one of the first observations that used the new KVN wide-band digital spectrometer, this consistency also gave confidence in its correct operation.

Spectral line properties of our H_2O maser detections, and upper limits for our SiO maser non-detections, are presented in Table 3. The observed sources are given in Column 1. The peak antenna temperatures of the H_2O masers and the 3σ upper limits of these temperatures of the SiO masers are given in Columns 2 and 3, respectively. Column 4 provides the integrated antenna temperatures. Columns 5 and 6 give the equivalent isotropic luminosities of the H_2O and SiO masers including their upper limits in terms of solar luminosity (cf., Bennert et al. 2009). For the latter estimations we used the integrated antenna temperatures, detection upper limits, and distances of Table 1, and assumed a SiO maser line width of 5 km s^{-1} similar to that of NGC 1068 (Wang et al. 2014).

The peak velocities of H_2O maser features towards each source are listed in Table 4. For five known H_2O maser sources (UGC 3193, UGC 3789, Antennae H_2O West, M 51, and NGC 6323), we did not detect H_2O maser emissions within our 3σ detection limits of between 0.018 K (0.22 Jy) and 0.027 K (0.33 Jy).

The SiO $v = 1,2$, $J = 1$–0 maser lines were not detected towards any of these ten sources at a 3σ detection limit of between $\sim$ 0.018 K (0.24 Jy) and $\sim$0.033 K (0.44 Jy). We expected that the SiO maser could be detected from the H_2O maser sources if their SiO maser photon luminosities were higher than the H_2O maser photon luminosities, as in the case of evolved stars in our Galaxy. The average values of SiO maser photon luminosities are higher than those of the H_2O photon luminosities in Mira variables and OH/IR stars of our Galaxy. For example, the average values of the SiO ($v = 1$, $J = 1$–0) photon luminosities of Mira variables are estimated to be $10^{43.1}$ photon s^{-1}($10^{-6.3}$ $L_\odot$), while those of H_2O photon luminosities are $10^{42.8}$ photon s^{-1}($10^{-6.6}$ $L_\odot$) (Kim et al. 2014). These results imply that the excitation condition of the SiO maser emission in the above five H_2O maser-detected sources is different from that of our Galactic evolved stars. This particular excitation condition of SiO masers may be supported by the detection of the $v = 3$, $J = 2$–1 maser emission in the Seyfert 2 galaxy NGC 1068 (Wang et al. 2014) in spite of the marginal detection of the SiO $v = 1$, $J = 2$–1 maser and non-detection of $v = 2$, $v =$ 2–1 maser. In our Galactic sources, SiO maser intensities normally decrease with increases in the vibrational state v for the same rotational transition J although the intensity of the SiO $v = 2$, $J = 1$–0 maser is stronger than that of the $v = 1$, $J = 1$–0 maser in fairly numerous post-AGB stars (Cho et al. 1996; Yoon et al. 2014). Specifically, the intensity ratios among $v = 1, 2, 3$, $J =$ 2–1 maser lines are $1 : 0.40 : 0.04$ for the sole SiO $v = 3$, $J = 2$–1 maser detected source χ Cyg (Cho et al. 2007). Wang et al. (2014) suggest that the SiO ($v = 3$, $J =$ 2–1) maser from the Seyfert 2 galaxy NGC 1068 likely originates from the nuclear disk and not from the hundreds of millions of χ Cyg like S-type Mira variables. One example of these different excitation conditions between AGNs and Galactic evolved stars may be a different radiation mechanism of infrared emission which is one of main factors of SiO maser pumping. Infrared emission from Galactic evolved stars is a thermal while that from AGNs is synchrotron radiation. This difference between them is well-known for optical emission lines (Veilleux & Osterbrock 1987).

Concerning the non-detection of the SiO maser emission from our observed extragalactic sources, excitation conditions and locations, SiO abundance, and sensitivity should be considered. The SiO maser emission induced by radiative and/or collisional pumping (Bujarrabal et al. 1994; Humphreys et al. 2002) requires very high temperatures (> 1000 K) and densities ($> 10^9$ cm^{-3}) for its excitation; the $v = 1$ state is 1770 K above the ground state (Elitzur et al. 1980) while the 22 GHz H_2O maser induced by collisional pumping (Yates et al. 1997) requires a temperature ranging from 300 K to 1000 K and densities ranging from 10^7 to 10^9 cm^{-3} (Benson & Little-Marenin 1996). Therefore, the SiO masers arise from a region close to the central stars, i.e., between 2 and 4 stellar radii in Galactic evolved stars (Diamond et al. 1994). These facts imply that the SiO masers from extragalactic sources also arise from regions of very high densities and temperatures, i.e., close to their galactic centers, for example, close to the AGNs; from the circumnuclear disk in the case of the NGC 1068 SiO maser emission. Furthermore, the abundance of SiO molecules in the nuclear region is enhanced by shocks and X-ray irradiation linked to nuclear activity as suggested by García-Burillo et al. (2010) in NGC 1068. They reported that the enhanced SiO abundance in the circumnuclear disk of NGC 1068 (García-Burillo et al. 2014, 350 pc -size) is approximately one to two orders of magnitude higher than that in the starburst ring with a 1–1.5 kpc radius. Therefore, the most likely regions of SiO maser emission could be located at the circumnuclear disk regions close to the AGN, in which sufficient gas is accreted from the outer disk and where the molecular outflows are likely driven by the AGN similar to the small-scale SiO maser emission in the Orion KL (Matthews et al. 2010; Vaidya & Goddi 2013). However, another important factor pertaining to the actual detection of SiO maser emissions will be the degree of a sensitivity. For the SiO maser detected source NGC 1068 (at 14.4 Mpc; Gallimore et al. 2001), the peak intensities are close to 4 mK (17 mJy) and 5.5 mK (23 mJy) in the $v = 1$, 3, $J = 2$–1 maser lines (Wang et al. 2014). Therefore, if the intensity ratio between the SiO $J = 1$–0 and $J = 2$–1 masers is assumed to be one in NGC 1068, we could not detect the SiO $v = 1$, 2, $J = 1$–0 masers from NGC 1068 within our upper limits of 0.024 K (0.32 Jy for $v = 1$) and 0.027 K (0.36 Jy for $v = 2$) using the KVN. An on-source integration time of approximately twelve hours is required to detect signals of SiO masers of approximately 0.021 Jy at 3σ noise levels from NGC 1068.

3.1. Comments on Three Individual Sources

NGC 1068: The H_2O maser emission from this prototypical Seyfert 2 barred galaxy was first detected by Claussen et al. (1984). As shown in Figure 1, we detected three H_2O maser features which correspondingly peaked at 855, 1125, and 1434 km s^{-1}. These three features are nearly symmetric with respect to the recessional velocity of the galaxy (V_{LSR} = 1137 km s^{-1}, Brinks et al. 1997). The maser feature which peaked at 1125 km s^{-1} is associated with the core of the compact radio source, S1 as the nuclear masers (Gallimore et al. 1996, 2001). The red-shifted masers peaked at 1434 km s^{-1} and blue-shifted masers peaked at 855 km s^{-1} about the systemic velocity are also nuclear masers. However, possibly due to variability, we could not detect the "jet masers" near 900 km s^{-1} which are associated with radio jet continuum feature C.

Table 4
Line Velocities of Detected H_2O Masers

Source	Peak velocities (Blue, Central, Red) (km s^{-1})
M 33	–229.75^C, –217.30^C, –208.99^C
NGC 1052	1690.3^C
NGC 1068	854.65^B
	1124.6^C
	1404.9^R, 1434.0^R
M 82	109.84^B, 348.11^R
NGC 4258	456.81^C, 489.20^C
	1267.1^R, 1315.9^R, 1347.6^R, 1406.7^R

Notes. ^{B} indicates Blue–shifted maser features, ^{C} Central maser features, and ^{R} Red-shifted maser features.

NGC 4258: The systemic H_2O maser features around the recessional velocity (V_{sys} = 672 km s^{-1}, Cecil et al. 1992) of the galaxy were initially detected by Claussen et al. (1984). The high-velocity features blue- and red-shifted with respect to the systemic velocity were discovered by Nakai et al. (1993). VLBI studies showed that maser emission originates from a rotating disk (Greenhill et al. 1995). A Keplerian rotation curve and warp in the disk structure were confirmed via VLBA observations (Miyoshi et al. 1995). This archetypal circumnuclear H_2O maser is used for measuring the accurate geometric distance to the active galaxy NGC 4258 (Argon et al. 2007; Humphreys et al. 2013). As shown in Figure 1, in 2011 February we could not detect blue-shifted maser features within our upper limits of 0.024 K. In addition, SiO $v = 1$, 2, J=1–0 masers were not detected around the velocity of the central H_2O maser features (around the systemic velocity of the galaxy) within our upper limits of 0.018 K (0.22 Jy).

M 82 (NGC 3034): The H_2O maser emission was initially detected by Claussen et al. (1984). The galaxy M 82 is a starburst galaxy undergoing a massive star-forming episode (Wills et al. 1999). A large-scale biconical outflow of hot gas was observed at X-ray and optical wavelengths from the nucleus of M 82 (Bregman et al. 1995; Shopbell & Bland-Hawthorn 1998). We detected blue- and red-shifted H_2O maser features with respect to the systemic velocity (V_{LSR} = 200 km s^{-1}). Hagiwara et al. (2004) associate these features with a molecular bipolar outflow. The broad feature occurring around V_{LSR} = 109 km s^{-1} showed flaring with a luminosity similar to the maximum luminosity observed in the Galactic star forming region W 49N (Baudry et al. 1994). In our observations, the red-shifted maser feature is narrow and shows a high intensity. The vertical filament feature of the SiO thermal emission with respect to the galaxy plane was referred to as the SiO chimney emanating from the disk by García-Burillo et al. (2001). They explained this in terms of shock chemistry driven by a violent gas ejection from the starburst disk. We could not detect the SiO $v = 1, 2, J = 1–0$ maser emission within our upper limits of 0.024 K (0.32 Jy for $v = 1$) and 0.027 K (0.36 Jy for $v = 2$).

3.2. Operation and Performance of Wide-Band Digital Spectrometer

The digital spectrometer of the KVN has two types of input ports and selects one of them depending on the operation mode; narrow-band or wide-band mode. In narrow-band mode, it uses one VLBI Standard Interface (VSI) input from a digital filter unit that has a total frequency bandwidth of 256 MHz. This mode is mainly used for spectroscopic observations requiring high spectral resolution. In wide-band mode, the spectrometer uses VSI inputs from four digital samplers, each offering a frequency bandwidth of 512 MHz. The digital spectrometer can produce a maximum of 8 spectra of 8192 channels each, and its control software can take only 4096 channels for each spectrum. In wide-band mode, we can take 4096 channels across whole 512 MHz bandwidth after smoothing or binning every 2 channels. We can also get 256 MHz (sub)bandwidth by selecting a continuous 4096 out of 8192 available channels. The latter was used for our observations. For details on the backend and its available modes see Oh et al. (2011).

We compared *rms* noise levels of spectra against values expected from system noise temperatures, integration time, quantization loss, and spectral resolution. We found that in 1–2 hour integrated spectra these are consistent within 6%. For the above comparison, we subtracted 1st or 2nd order polynomial baselines from the spectra. The measured *rms* noise levels were 4% higher than the expected values on average. There was no noticeable change in the excess noise ratio with the integration time from one minute to two hours. We confirmed that the *rms* noise levels decrease with $1/\sqrt{\tau}$, where τ is the integration time. This indicates that the noise of a spectrum is dominated by random noise, and contribution of systemic noise such as residual baselines or spurious signals is much less than that of random noise components.

4. SUMMARY

We undertook simultaneous observations of H_2O and SiO masers toward ten known extragalactic H_2O maser sources in February 2011 using the Korean VLBI Network (KVN) single dish telescope. We also aimed at testing the performance of a wide band digital spectrometer at first stage of its operation. The results are summarized below.

1. We detected the 22 GHz H_2O maser emission from five known extragalactic H_2O maser sources; M 33, NGC 1052, NGC 1068, NGC 4258, and M 82. However, from another five known extragalactic H_2O maser sources; UGC 3193, UGC 3789, Antennae (H_2O W), M 51, and NGC 6323, we could not detect the H_2O maser emission within 3σ upper limits of 0.018–0.027 K (0.22–0.33 Jy).
2. The detected H_2O maser lines of five known extragalactic H_2O maser sources exhibit central features around their systemic velocities and/or blue- and red-shifted features according to their originality as is previously known (i.e., central features around systemic velocities from spiral galaxy M 33 and elliptical galaxy NGC 1052, central features together with blue- and red-shifted features from Seyfert 2 galaxy NGC 1068, central features together with red-shifted features from the Seyfert 2 galaxy NGC 4258, and blue- and red-shifted features from the starburst galaxy M 82). The blue-shifted features from NGC 4258 were not detected within the upper limits of 0.024 K (0.29 Jy).
3. We could not detect the SiO $v = 1, 2, J = 1–0$ maser emission from any of the ten known extragalactic H_2O maser sources within our upper limits of 0.018 K–0.033 K (0.24 Jy–0.44 Jy). The SiO maser emission in extragalactic sources is very faint or rare compared to the H_2O maser. An on-source integration time of more than twelve hours is required to detect the ~20 mJy level SiO maser emission similar to that of NGC 1068 using the KVN single dish telescope.
4. We confirmed that the digital spectrometer of the KVN is properly working in wide-band mode and the 22 GHz and 43 GHz receivers are stable enough to provide good baselines characteristics well fitted with first or second order polynomials over a 256 MHz frequency bandwidth. The detected H_2O maser spectral features from five known extragalactic H_2O maser sources are consistent with earlier detections. As one of the first observations that used the new KVN wide-band digital spectrometer, this consistency gave confidence in the correct operation of the new spectrometer.

ACKNOWLEDGMENTS

This work was supported by the Basic and Fusion Research Programs (2011–2015) and also partially supported by the KASI–Yonsei Joint Research Program entitled the "Degree and Research Center Program" funded by the National Research Council of Science and Technology (NST). We are grateful to all of the staff members at KVN who helped to operate the array, operate the single dish telescope, and to correlate the data. The KVN is a facility operated by KASI (Korea Astronomy and Space Science Institute). The KVN operations are supported by KREONET (Korea Research Environment Open NETwork) which is managed and operated by KISTI (Korea Institute of Science and Technology Information).

REFERENCES

Argon, A. L., Greenhill, L. J., Reid, M. J., Moran, J. M., & Humphreys, E. M. L. 2007, Toward a New Geometric Distance to the Active Galaxy NGC 4258. I. VLBI Monitoring of Water Maser Emission, ApJ, 659, 1040

Baudry, A., Brouillet, N., & Henkel, C. 1994, H_2O Activity in M 82 and in Other Members of the M 81 Group, A&A, 287, 20

Bennert, N., Barvainis, R., Henkel, C., & Antonucci, R. 2009, A Search for H_2O Megamasers in High-z Type-2 Active Galactic Nuclei, ApJ, 695, 276

Benson, P. J., & Little-Marenin, I. R. 1996, Water Masers Associated with Circumstellar Shells, ApJS, 106, 579

Braatz, J. A., & Gugliucci, N. E. 2008, The Discovery of Water Maser Emission from Eight Nearby Galaxies, ApJ, 678, 96

Bregman, J. N., Schulman, E., & Tomisaka, K. 1995, High-Resolution X-Ray Imaging of the Starburst Galaxy M 82, ApJ, 439, 155

Brinks, E., Skillman, E. D., Terlevich, R. J., & Terlevich, E. 1997, HI Observations of NGC 1068, Ap&SS, 248, 23

Brogan, C., Johnson, K., & Darling, J. 2010, Water Masers Associated with Star Formation in the Antennae Galaxies, ApJ, 716, L51

Bujarrabal, V. 1994, Numerical Calculations of SiO Maser Emission I. Intensity and Variability, A&A, 285, 953

Cecil, G, Wilson, A. S., & Tully, R. B. 1992, The Braided Jets in the Spiral Galaxy NGC 4258, ApJ, 390, 365

Claussen, M. J., Heiligman, G. M., & Lo, K. Y. 1984, Water-Vapor Maser Emission from Galactic Nuclei, Nature, 310, 298

Cho, S.-H., Kaifu, N., & Ukita, N. 1996, SiO Maser Survey of Late-Type Stars. II. Statistical Study, AJ, 111, 1987

Cho, S.-H., Lee, C. W., & Park, Y.-S. 2007, First Detection of the SiO ($v = 3$, $J = 2$–1) Maser Emission from χ Cygni, ApJ, 657, 482

Churchwell, E., et al. 1977, Detection of H_2O Maser Emission in the Galaxy M 33, A&A, 54, 969

Diamond, P. J., Kemball, A. J., Junor, W., Zensus, A., Benson, J., & Dhawan, V. 1994, Observation of a Ring Structure in SiO Maser Emission from Late-Type Stars, ApJ, 430, 61

Elitzur, M. 1980, The Nature of SiO Masers in Late-Type Stars, ApJ, 240, 553

Gallimore, J. F., Baum, S. A., & O'Dea, C. P. 1996, The Subarcsecond Radio Structure in NGC 1068. II. Implications for the Central Engine and Unifying Schemes, ApJ, 464, 198

Gallimore, J. F., Henkel, C., Baum, S. A., et al. 2001, The Nature of the Nuclear H_2O Masers of NGC 1068: Reverberation and Evidence for a Rotating Disk Geometry, ApJ, 556, 694

García-Burillo, S., Martn-Pintado, J., Fuente, A., & Neri, R. 2001, SiO Chimneys and Supershells in M 82, ApJ, 563, 27

García-Burillo, S., Usero, A., Fuente, A., et al. 2010, Molecular Gas Chemistry in AGN. II. High-Resolution Imaging of SiO Emission in NGC 1068: Shocks or XDR?, A&A, 519, 2

García-Burillo, S., Combes, F., Usero, A., et al. 2014, Molecular Line Emission in NGC 1068 Imaged with ALMA. I. An AGN-Driven Outflow in the Dense Molecular Gas, A&A, 567, 125

Greenhill, L. J., Jiang, D. R., Moran, J. M., Reid, M. J., Lo, K. Y., & Claussen, M. J. 1995, Detection of a Subparsec Diameter Disk in the Nucleus of NGC 4258, ApJ, 440, 619

Hagiwara, Y. 2004, VLA Imaging of H_2O Masers in NGC 6240 and M 82, ASPC, 320, 179

Han, S.-T., Lee, J.-W., Kang, J., et al. 2008, Millimeter-Wave Receiver Optics for Korean VLBI Network, Int. J Infrared Milli Waves, 29, 69

Han, S.-T., Lee, J.-W., Kang, J., et al. 2013, Korean VLBI Network Receiver Optics for Simultaneous Multi-Frequency Observation: Evaluation, PASP, 125, 539

Humphreys, E. M. L., Gray, M. D., Yates, J. A., Field, D., Bowen, G. H., & Diamond, P. J. 2002, Numerical Simulations of Stellar SiO Maser Variability. Investigation of the Effect of Shocks, A&A, 386, 256

Humphreys, E. M. L., Reid, M. J., Moran, J. M., Greenhill, L. J., & Argon, A. L. 2013, Toward a New Geometric Distance to the Active Galaxy NGC 4258. III. Final Results and the Hubble Constant, ApJ, 775, 13

Impellizzeri, C. 2008, Molecular Absorption in the Cores of AGN: On the Unified Model, Bonn University dissertations

Kim, J., Cho, S.-H., & Kim, S. J. 2014, Statistical Studies Based on Simultaneous SiO and H_2O Maser Surveys toward Evolved Stars, AJ, 147, 22

Klockner, H.-R., & Baan, W. A. 2004, An Embedded Circumnuclear Disk in Mrk 273, A&A, 419, 887

Kuo, C. Y., Braatz, J. A., & Condon, J. J., et al. 2011, The Megamaser Cosmology Project. III. Accurate Masses of Seven Supermassive Black Holes in Active Galaxies with Circumnuclear Mega-Maser Disks, ApJ, 727, 20

Lee, S. S., Byun, D.-Y., & Oh, C. S., et al. 2011, Single-Dish Performance of KVN 21 m Radio Telescopes: Simultaneous Observations at 22 and 43 GHz, PASJ, 123, 1398

Lo, K. Y. 2005, Mega-Maser and Galaxies, ARA, 43, 625

Matthews, L. D., Greenhill, L. J., Goddi, C., et al. 2010, A Feature Movie of SiO Emission 20-100 AU from the Massive Young Stellar Object Orion Source I, ApJ, 708, 80

Miyoshi, M., Moran, J., Herrnstein, J., et al. 1995, Evidence for a Black Hole from High Rotation Velocities in a Subparsec Region of NGC 4258, Nature, 373, 127

Nakai, N., Inoue, M., & Miyoshi, M. 1993, Extremely-High-Velocity H_2O Maser emission in the Galaxy NGC 4258, Nature, 361, 45

Oh, S.-J., Roh, D.-G., Wajima, K., et al. 2011, Design and Development of a High-Speed DAS for the KVN, PASJ, 1229, 63

Reid, M. J., Braatz, J. A., Condon, J. J., et al. 2009, The Megamaser Cosmology Project. I. Very Long Baseline Interferometric Observations of UGC 3789, ApJ, 695, 287

Shopbell, P. L., & Bland-Hawthorn, J. 1998, The Asymmetric Wind in M 82, ApJ, 493, 129

Tarchi, A. 2012, in IAU Symposium, Vol. 287, IAU Symposium, ed. R. S. Booth, W. H. T. Vlemmings, & E. M. L. Humphreys, 323

Vaidya, B., & Goddi, C. 2013, MHD Modeling of a Disc Wind from a High-Mass Protobinary: the Case of Orion Source I, MNRAS, 429, L50

van Loon, J. T., Zijlstra, A. A., Bujarrabal, V., & Nyman, L.-A. 1996, Discovery of the First Extragalactic SiO Maser, A&A, 306, L29

Veilleux, S., & Osterbrock, D. E. 1987, Spectral Classification of Emission-Line Galaxies, ApJS, 63, 295

Wagner, J. 2013, 22 GHz Water Maser Search in 37 Nearby Galaxies: Four New Water Megamasers in Seyfert 2 and

OH Maser/Absorber Galaxies, A&A, 560, 12
Wang, J., Zhang, J., Gao, Y., et al. 2014, SiO and CH_3OH Megamaser in NGC 1068, Nature, 5, 5449
Wills, K. A., Redman, M. P., Muxlow, T. W. B., & Pedlar, A. 1999, Chimneys in the Starburst Galaxy M 82, MNRAS, 309, 395
Yates, J. A., Field, D., & Gray, M. D. 1997, Non-Local Radiative Transfer for Molecules: Modeling Population Inversions in Water Masers, MNRAS, 285, 303
Yoon, D.-H., Cho, S.-H., Kim, J., Yun, Y. J., & Park, Y.-S. 2014, SiO and H_2O Maser Survey toward Post-Asymptotic Giant Branch and Asymptotic Giant Branch Stars, ApJS, 211, 15