



Micro et nano-antennes adaptées à la microscopie champ proche et à l'imagerie haute résolution

Audrey FAHYS

Vendredi 7 décembre 2007

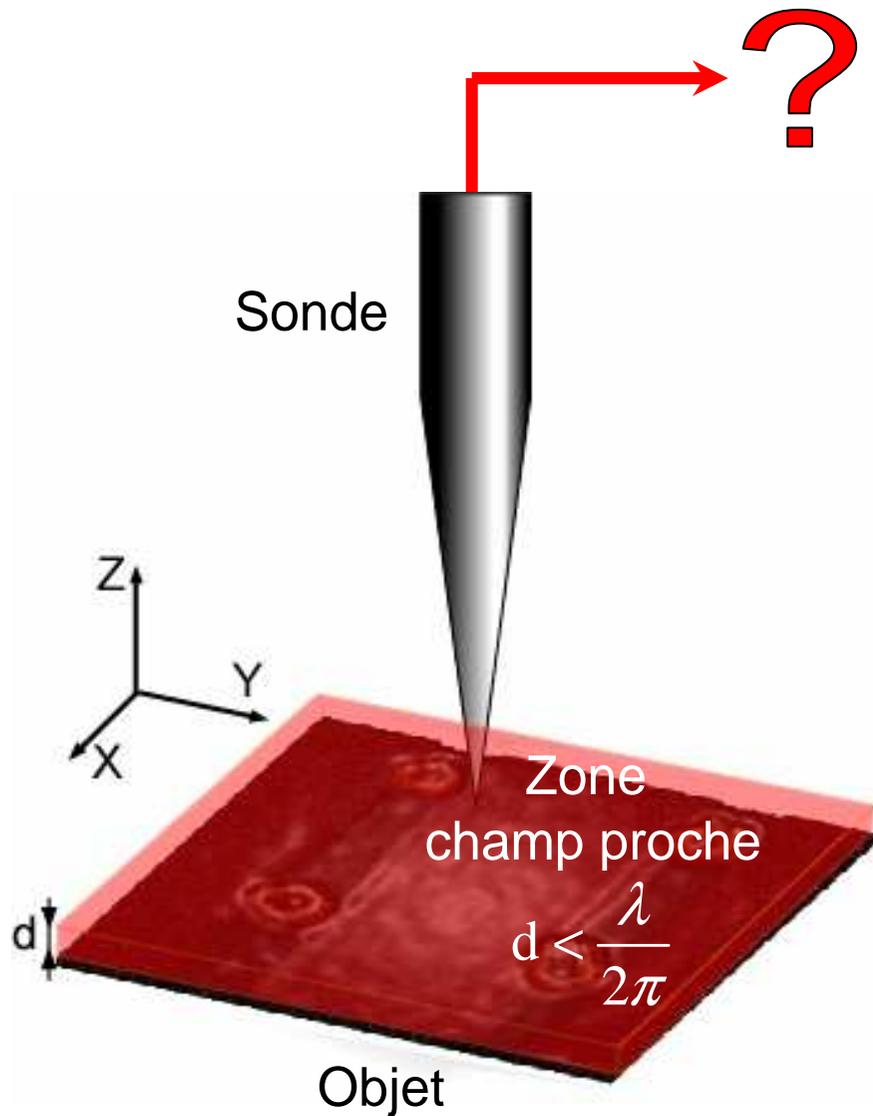
**Institut FEMTO-ST
Département d'Optique P.M. Duffieux**



- Microscopie en champ proche & Antennes
 - les sondes
 - les antennes
 - les faisceaux de Bessel polarisés
 - choix de l'antenne
- Techniques de fabrication
 - thermo-étirage & autres techniques
 - polissage & métallisation
 - usinage FIB
- Validation & Tests
 - caractérisation des nano-antennes
 - premiers tests en imagerie
- Conclusion & Perspectives

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Microscopie optique en champ proche

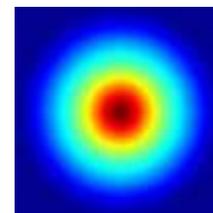


Détection :
 $|E_x|^2$, $|E_y|^2$ ou $|E_z|^2$
 $|H_x|^2$, $|H_y|^2$ ou $|H_z|^2$
Combinaison des champs

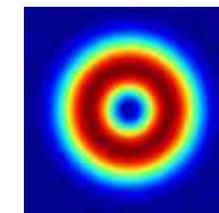
Répondre à cette question

=> meilleure interprétation des images optiques champ proche

Discriminer **E** et **H** ?



$|E|^2$



$|H|^2$

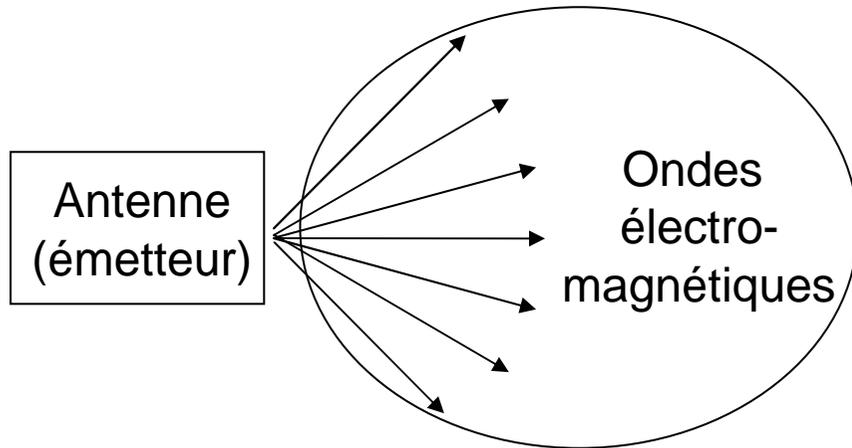
Élément clef : **la sonde**

Paramètres critiques :

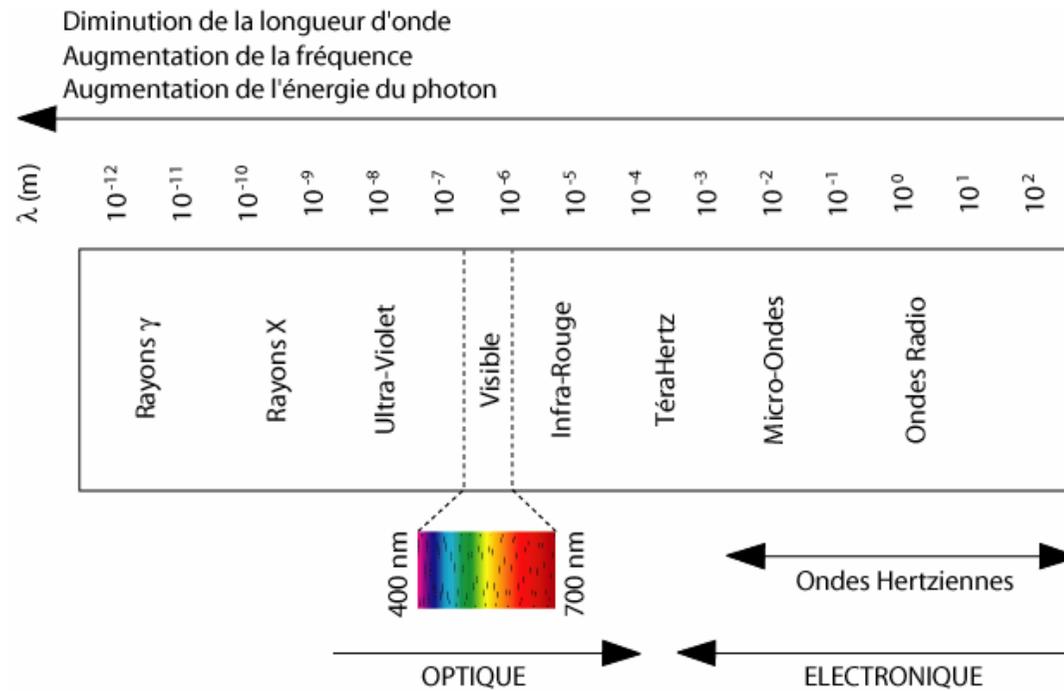
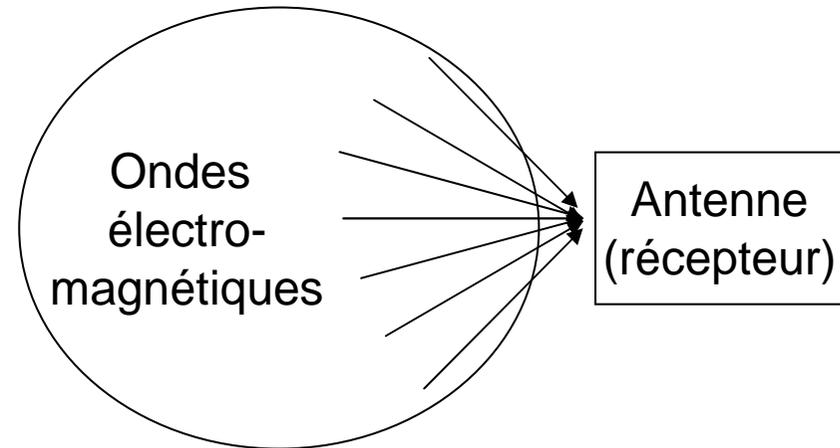
- ▶ Dimension et qualité de l'extrémité
 - résolution spatiale du microscope
- ▶ Angle d'ouverture du cône
 - efficacité d'émission ou de collection
- ▶ Reproductibilité de fabrication des pointes
 - interprétation des images

Qu'est-ce qu'une antenne ?

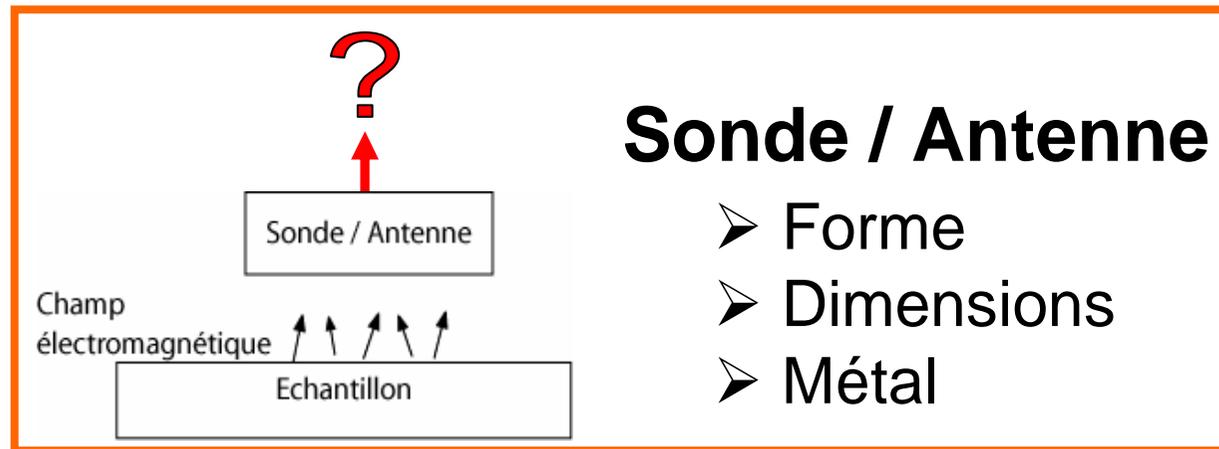
Systeme rayonnant :



Systeme capteur :



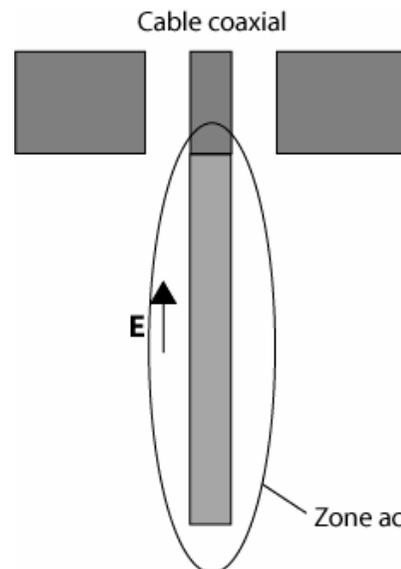
Les antennes



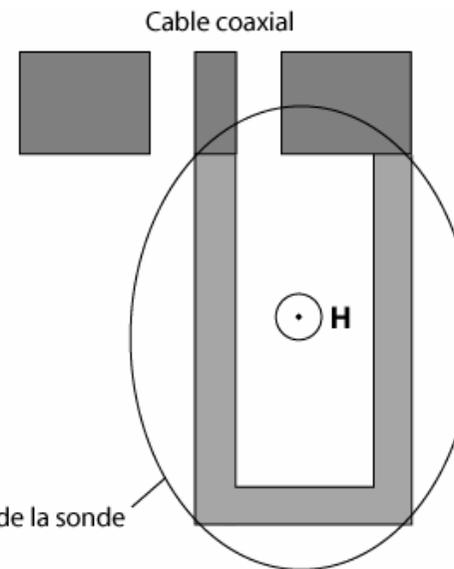
Détection du champ **électrique**

Détection du champ **magnétique**

**Antenne
filaire**

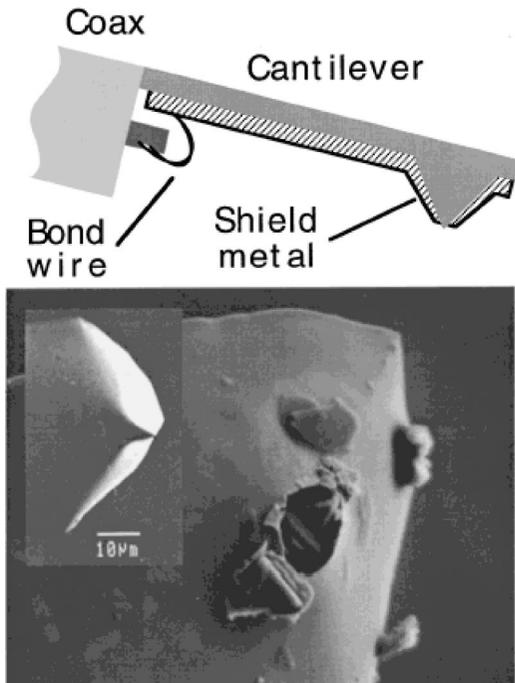


**Antenne
annulaire**



Les antennes : exemples

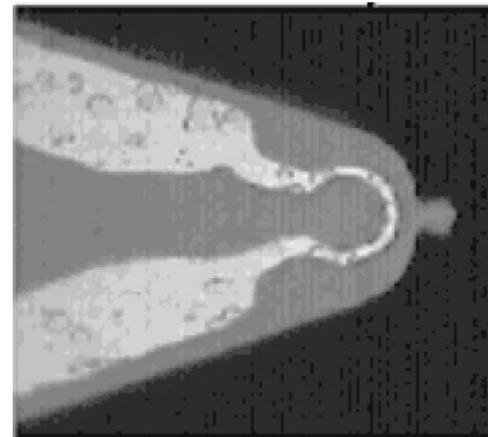
Microscopie micro-onde en champ proche



D.W. van der Weide,
APL **70**, 677 (1997).



Détection du champ **électrique**



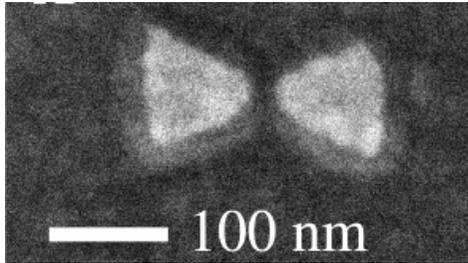
V. Agrawal & al.,
APL **71**, 2343 (1997).



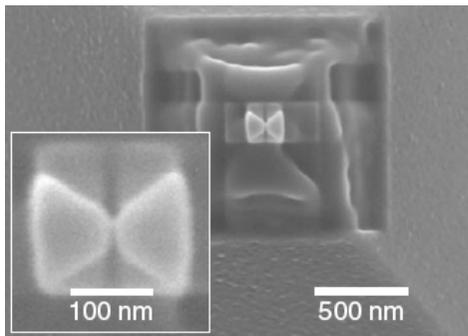
Détection du champ **magnétique**

Les antennes : exemples

Microscopie optique en champ proche



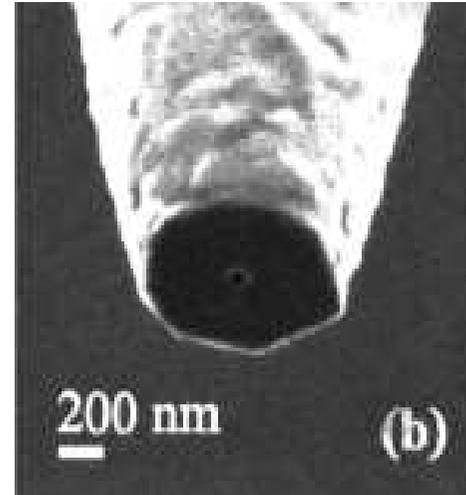
D. Fromm & al.
Nano Lett. 4, 957 (2004).



J.N. Farahani & al.
PRL 95, 017402 (2005).



Détection du champ **électrique**



J.A. Veerman & al.
APL 72, 3115 (1998).

E. Devaux & al.
PRB 62, 10504 (2000).



Détection du champ **magnétique**

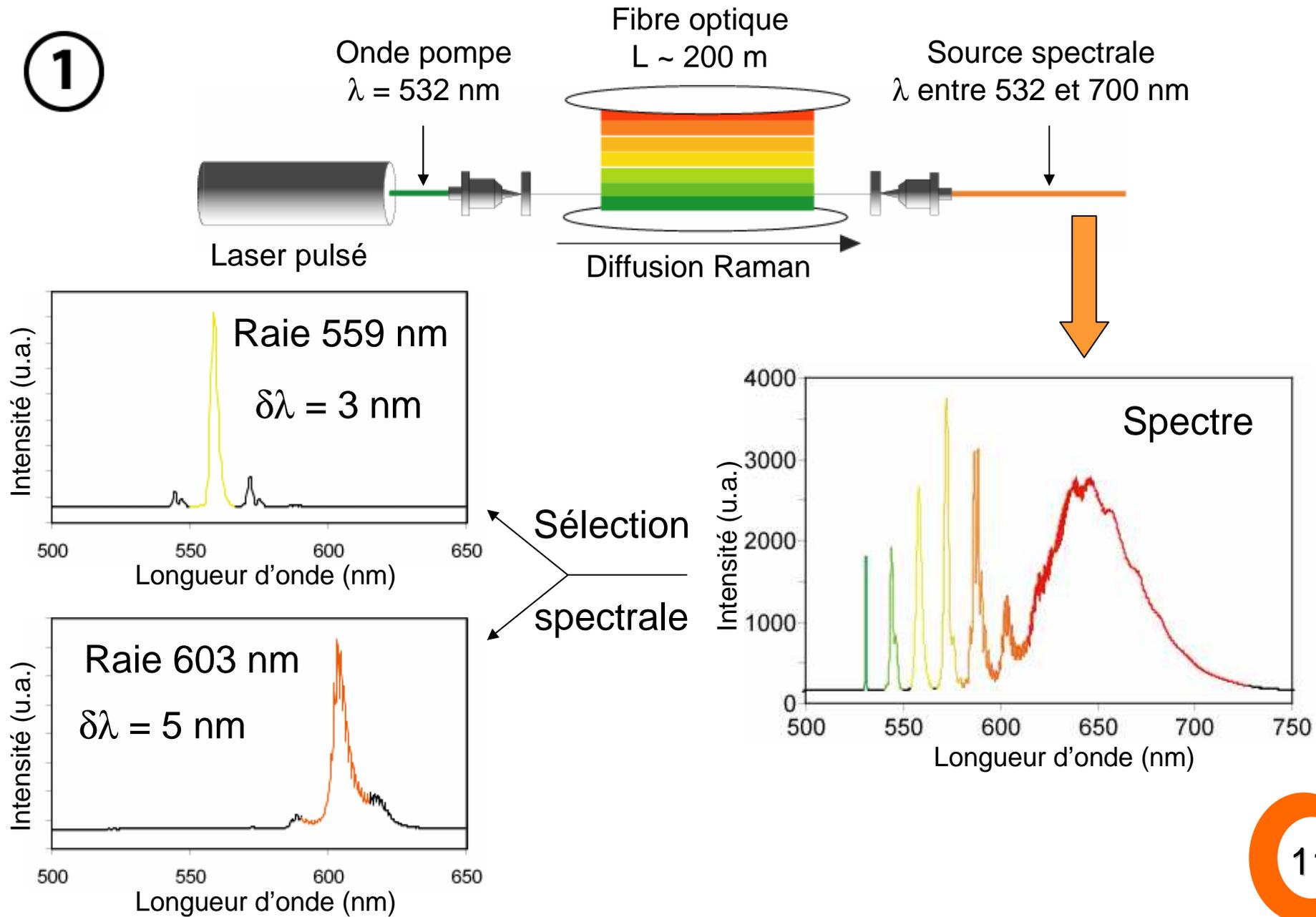
Configuration retenue

Outils de caractérisation des sondes

- ① Source : continuum
- ② Polarisations : radiale & orthoradiale
- ③ Faisceaux de Bessel polarisés

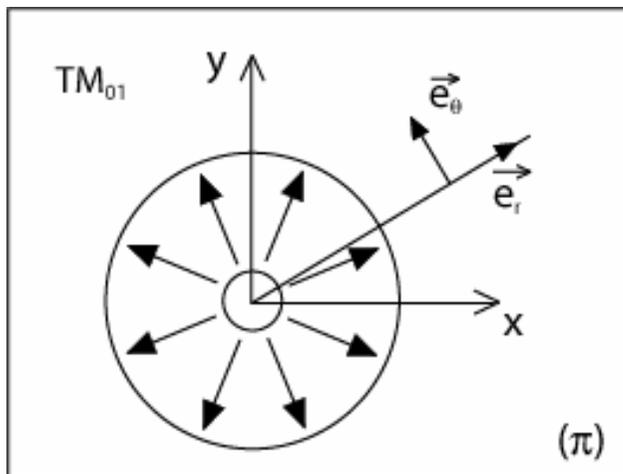
Continuum

1



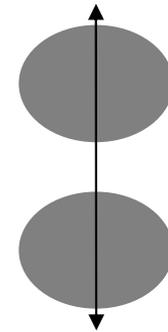
Polarisation

②

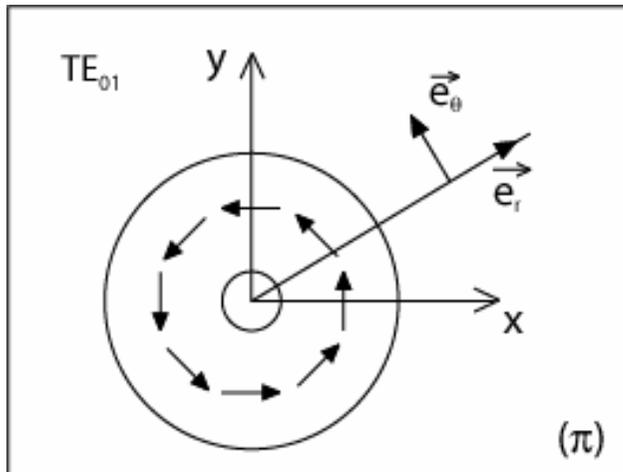


Polarisation **radiale** :

$$E_{TM} = F(r) \{ \cos \phi \hat{x} + \sin \phi \hat{y} \}$$

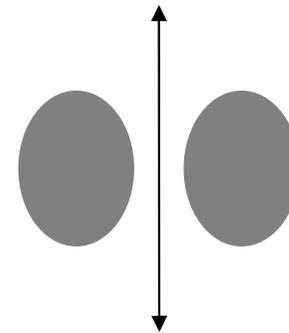


Axe du polariseur



Polarisation **orthoradiale** :

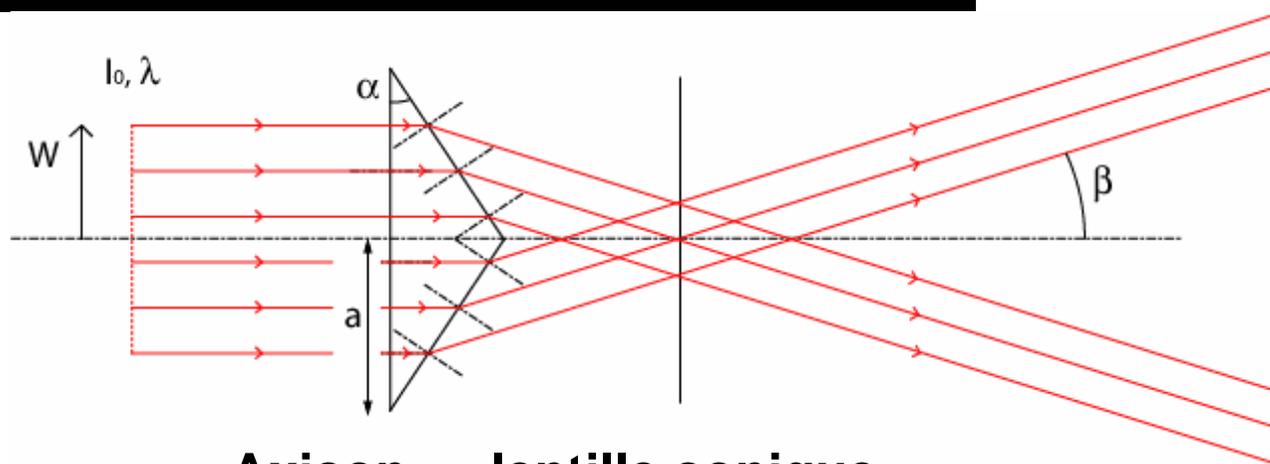
$$E_{TE} = F(r) \{ \sin \phi \hat{x} - \cos \phi \hat{y} \}$$



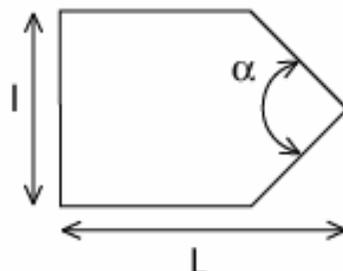
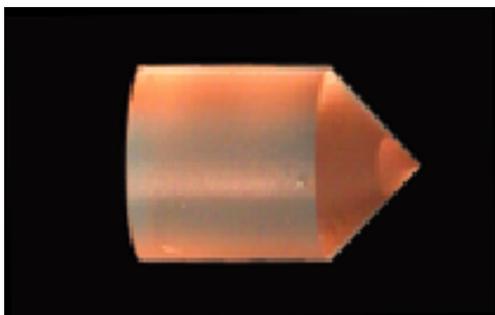
Faisceaux de Bessel

3

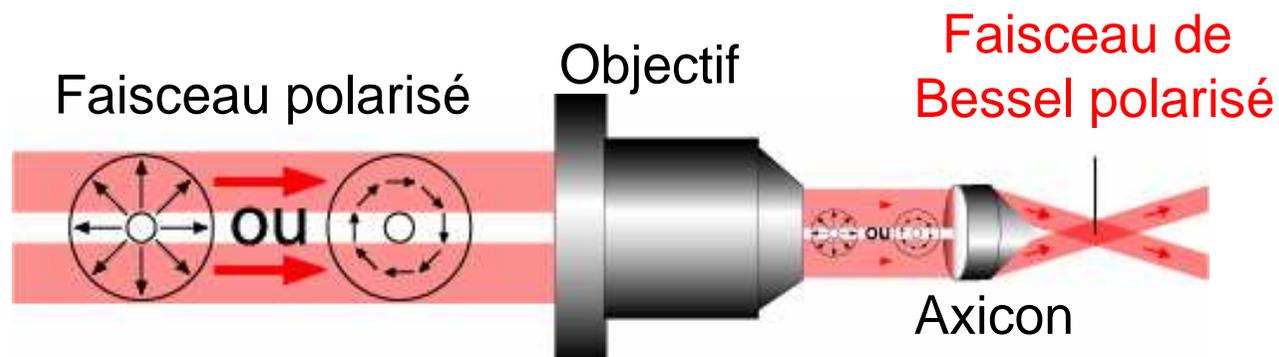
Principe :



Axicon ↔ lentille conique



$L = 7,5 \text{ mm} \pm 0,1 \text{ mm}$
 $l = 5 \text{ mm} \pm 0,05 \text{ mm}$
 $\alpha = 90^\circ \pm 6'$



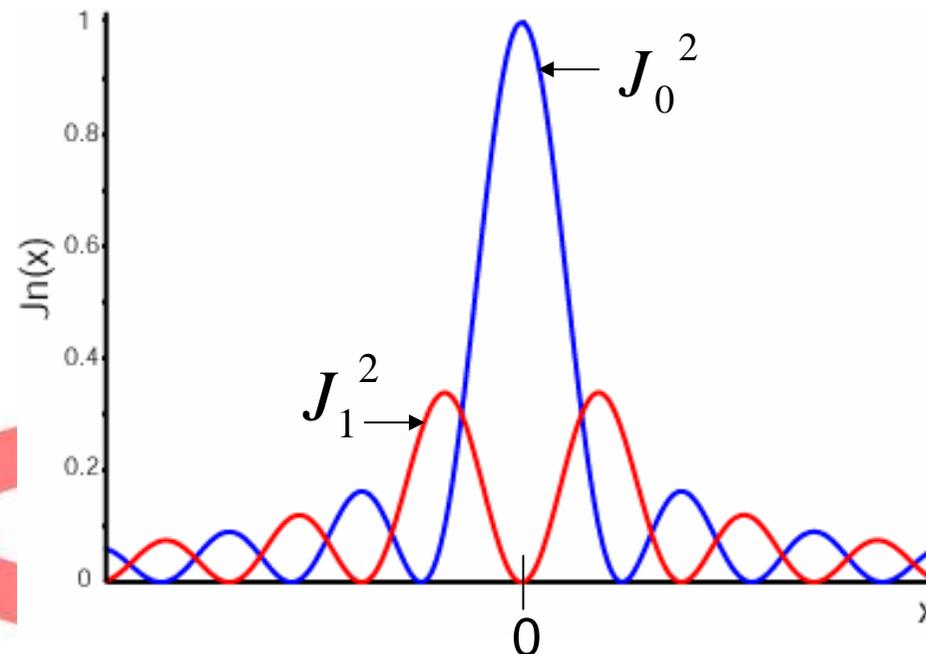
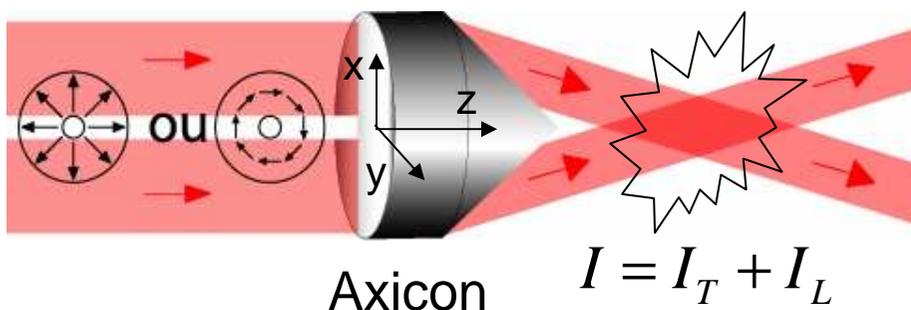
Faisceaux de Bessel polarisés

Polarisation radiale

$$E_x(\rho, \xi) \propto -i \cos \theta \cos \xi J_1(\alpha \rho)$$

$$E_y(\rho, \xi) \propto -i \cos \theta \sin \xi J_1(\alpha \rho)$$

$$E_z(\rho, \xi) \propto \sin \theta J_0(\alpha \rho)$$



Composante **transverse**

Composante **longitudinale**

Radiale $I_T = |E_x|^2 + |E_y|^2 \propto J_1^2$

$$I_L = |E_z|^2 \propto J_0^2$$

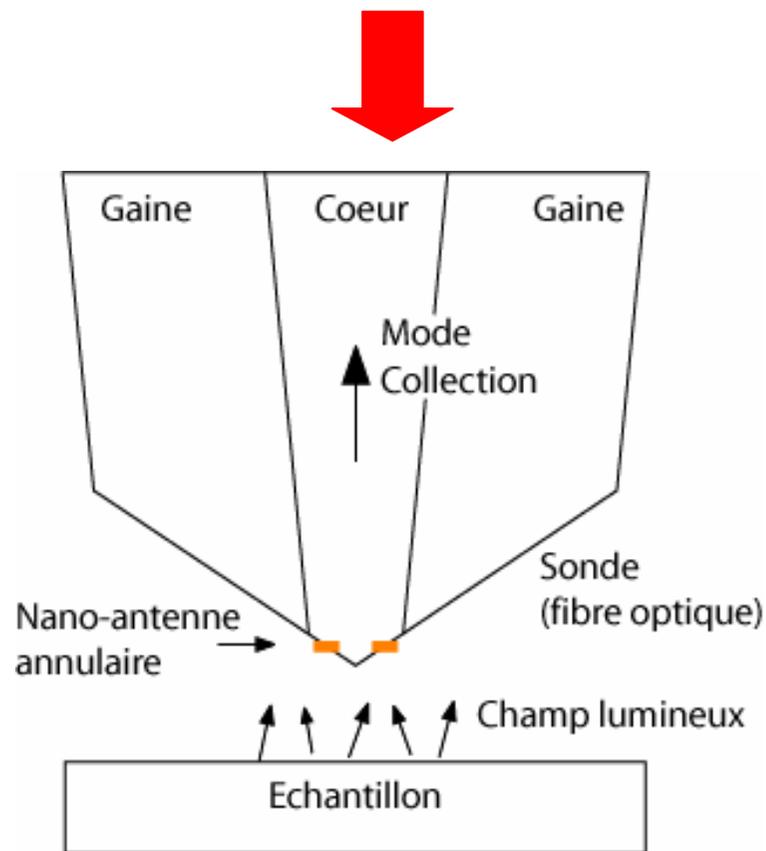
Orthoradiale $I_T = |H_x|^2 + |H_y|^2 \propto J_1^2$

$$I_L = |H_z|^2 \propto J_0^2$$

Choix de l'antenne

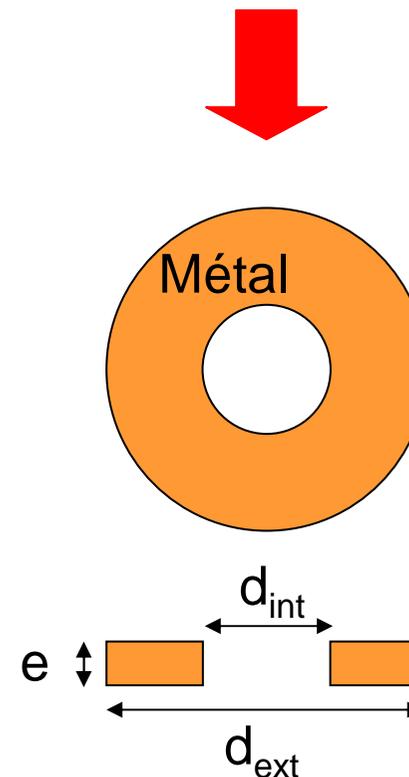
But : nanostructure à l'extrémité d'une sonde

Support
fibre optique



Antenne

Forme simple : anneau
Dimensions réalistes



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Transposition à une échelle submicrométrique

Sonde :

- centrage de l'extrémité sur l'axe du cœur
- qualité de surface (faible rugosité)
- définition de l'extrémité (sublongueur d'onde)

Nanostructure annulaire :

- choix de la structure
- dimensions spécifiques
- usinage sur une surface non plane
- centrage de la structure sur l'axe du cœur

Techniques de préparation des sondes

Exemples de sondes

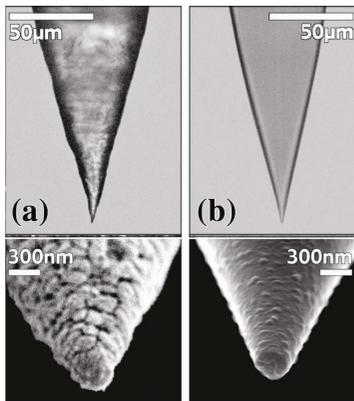
Usinage chimique

Microfabrication

Pointe simple taper

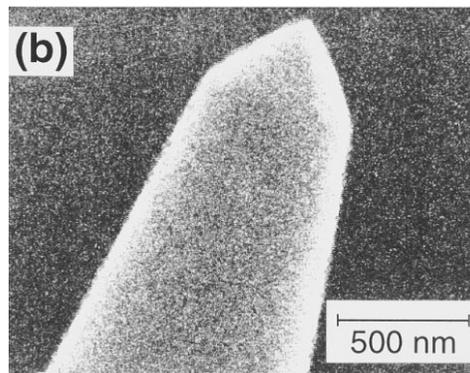
Pointe double taper

Sonde hybride



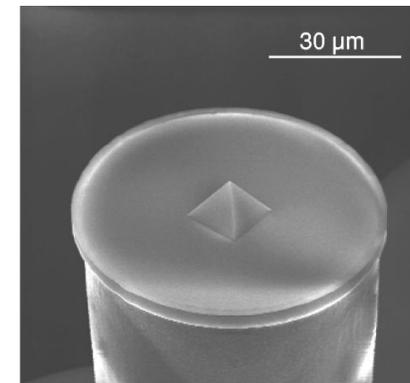
R. Stöckle & al.
APL 75, 160 (1999).

$\theta \sim 20^\circ$



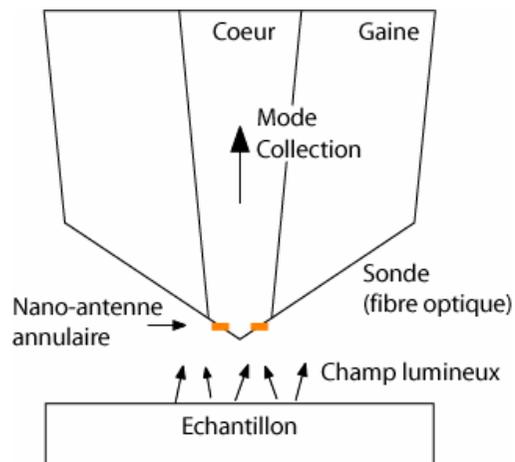
T. Saiki & al.
APL 74, 2773 (1999).

$\theta \sim 90^\circ$



G. Genolet & al.
RSI 72, 3877 (2001).

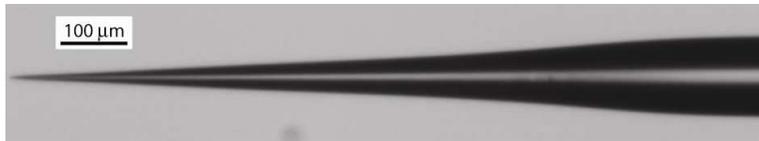
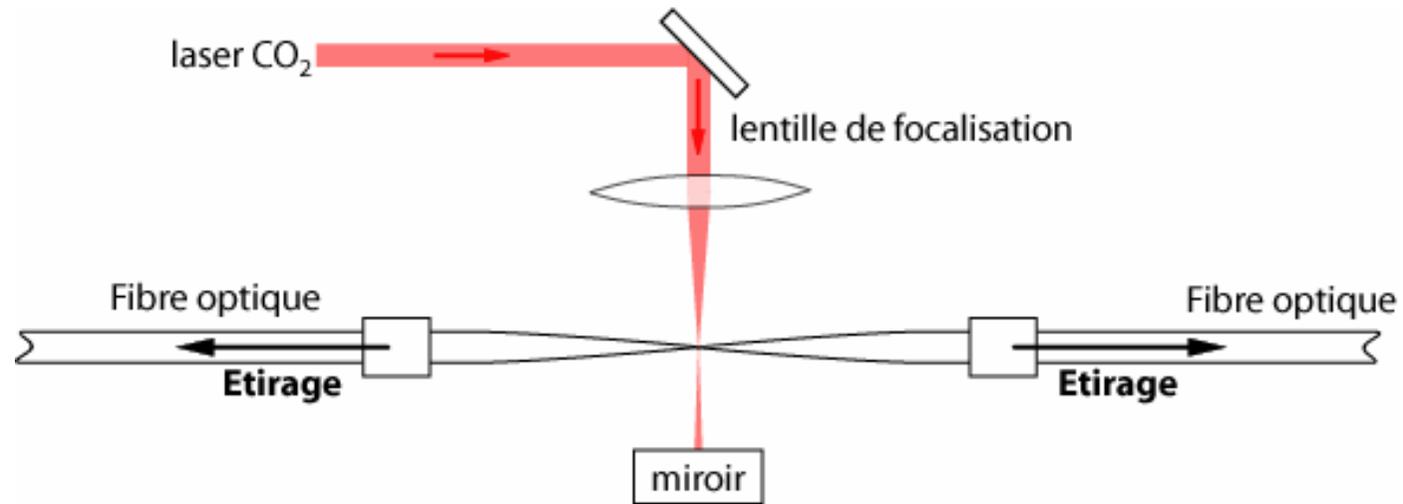
Etapes de fabrication



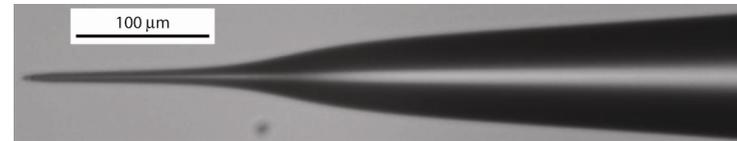
- ① Thermo-étirage
- ② Polissage
- ③ Métallisation
- ④ Usinage FIB (Focused Ion Beam)

Méthode de chauffage et étirage

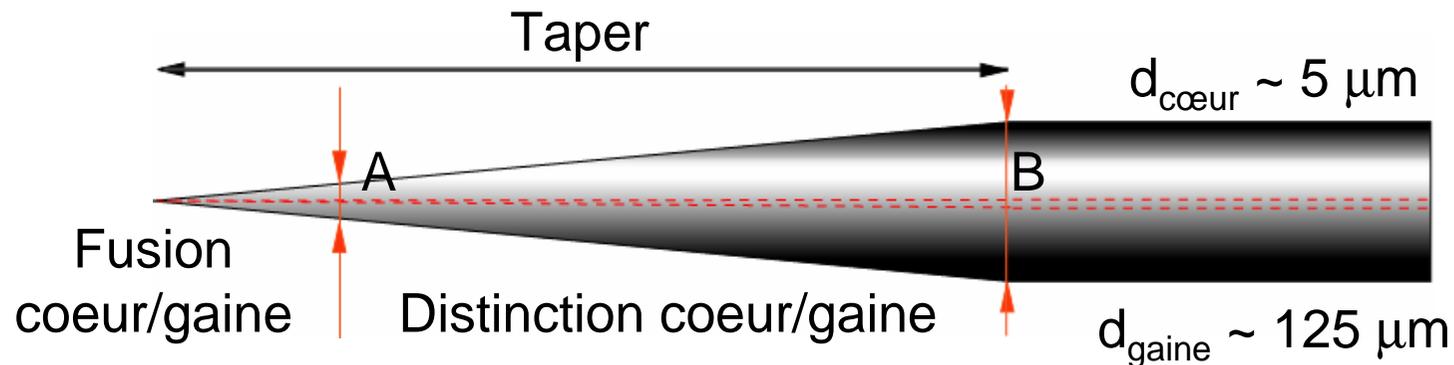
1



$\theta \sim 10^\circ$

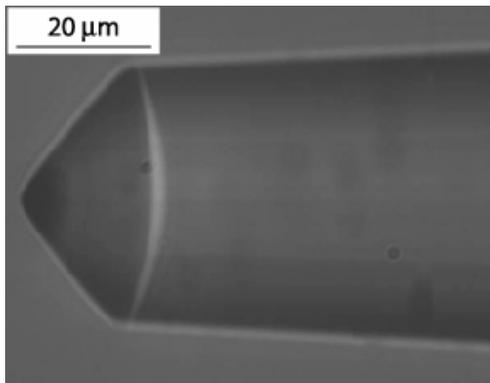
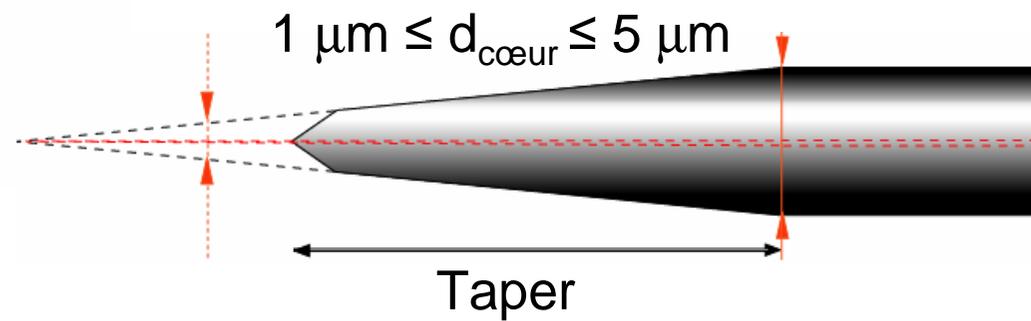
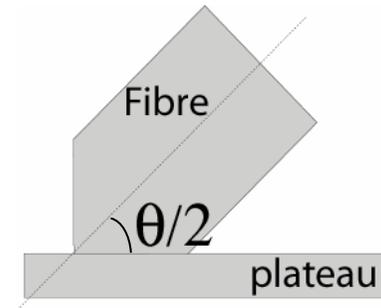
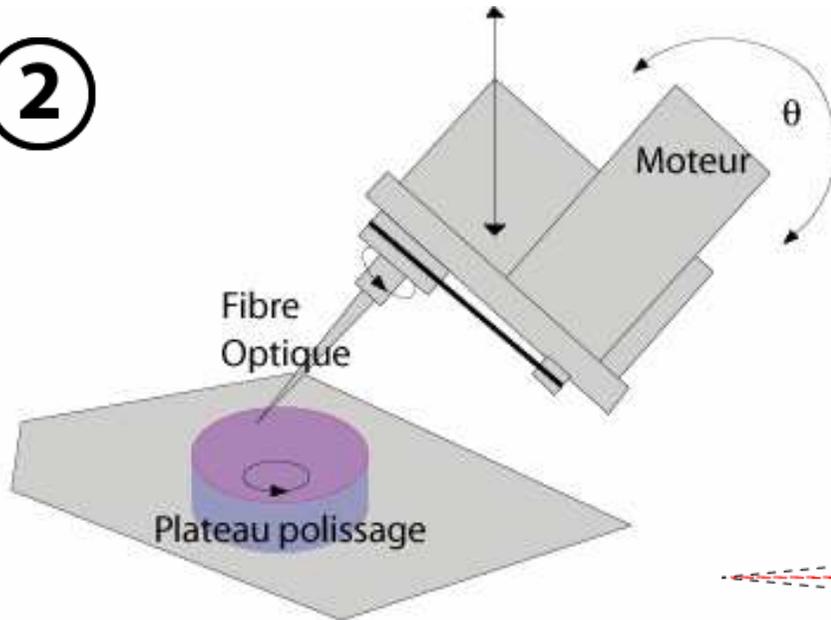


Sondes effilées



Technique de polissage

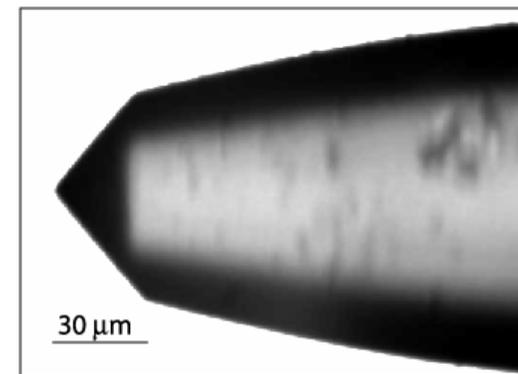
②



$d_{\text{cœur}} \sim 1,5 \mu\text{m}$

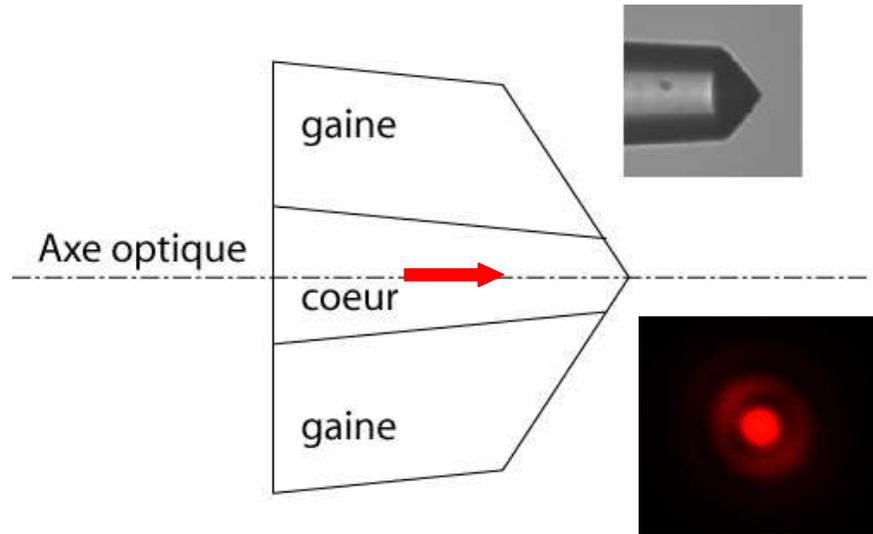
$\theta = 100^\circ$

Sondes micro-axicons

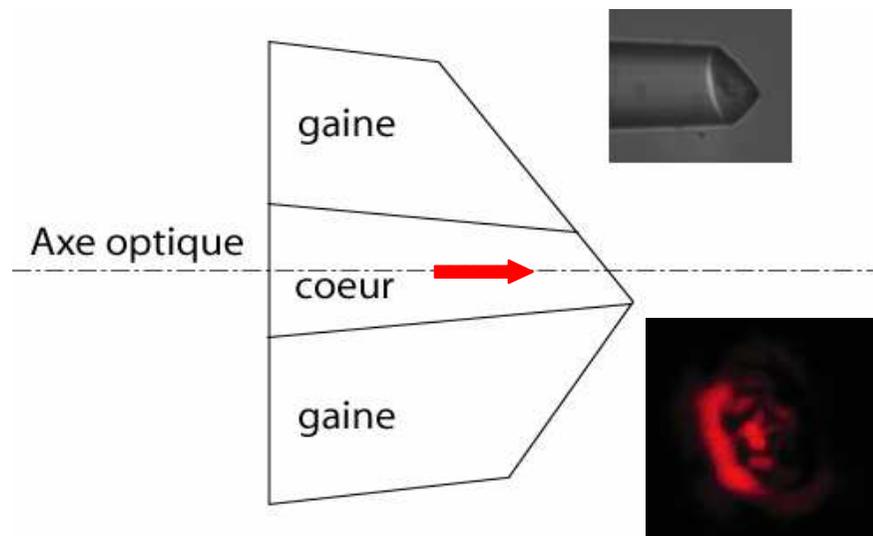


$d_{\text{cœur}} \sim 2,6 \mu\text{m}$

Micro-axicon opérationnel ?

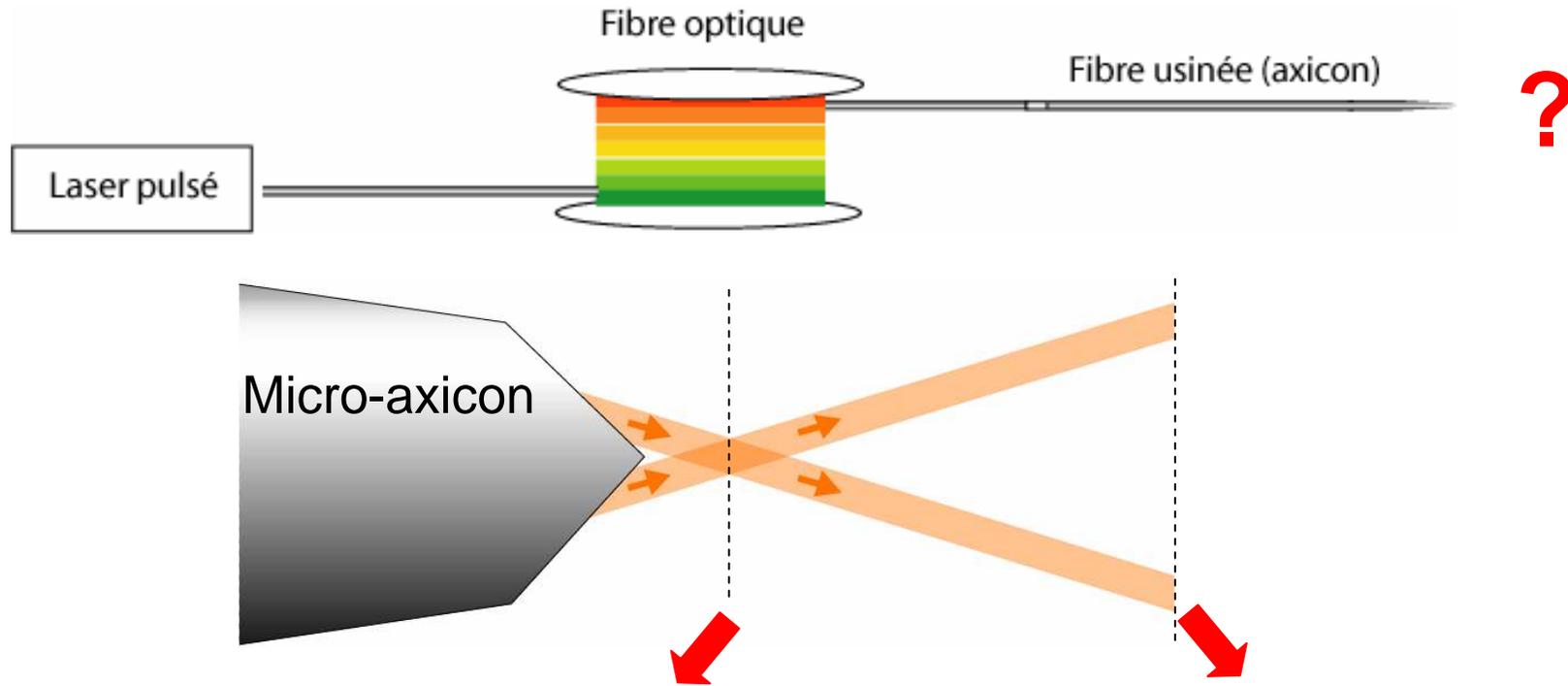


OUI



NON

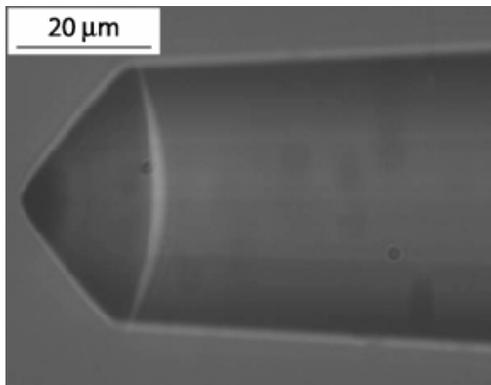
Micro-axicon opérationnel



Faisceau de Bessel

Anneau de diffraction

Fabrication sur fibre optique d'un micro-axicon

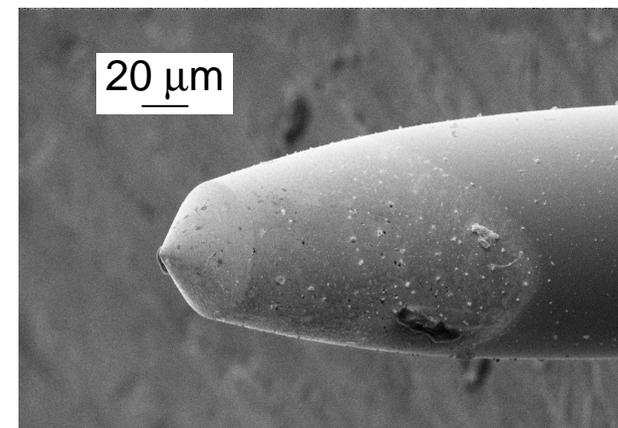
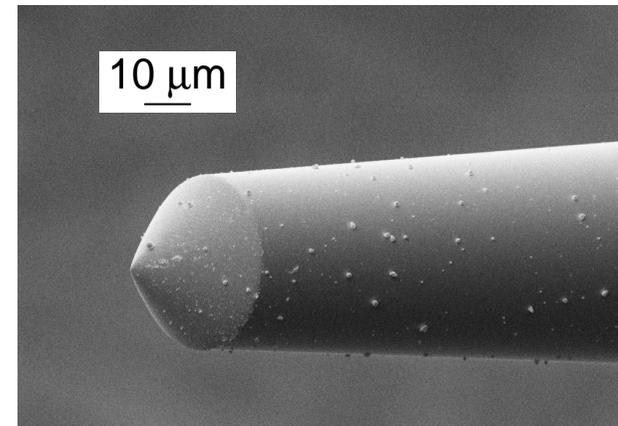
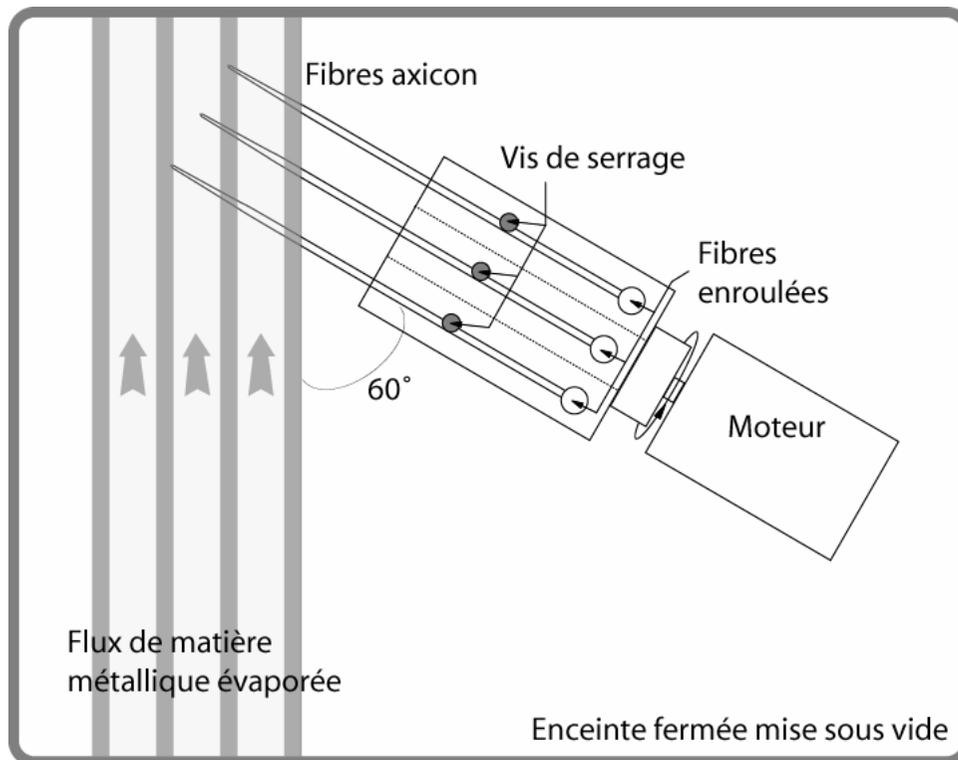


- centrage de l'extrémité sur l'axe du cœur
- qualité de surface
- contrôle de l'angle d'ouverture
- contrôle du diamètre du cœur

Métallisation

3

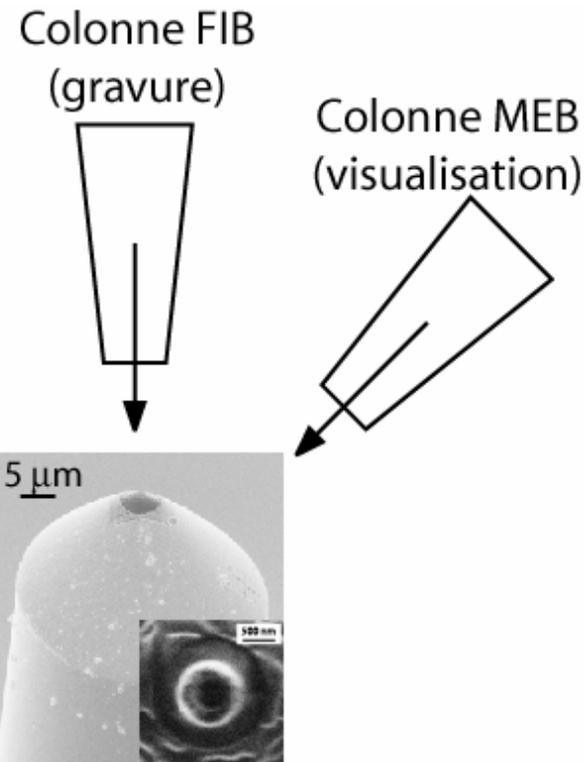
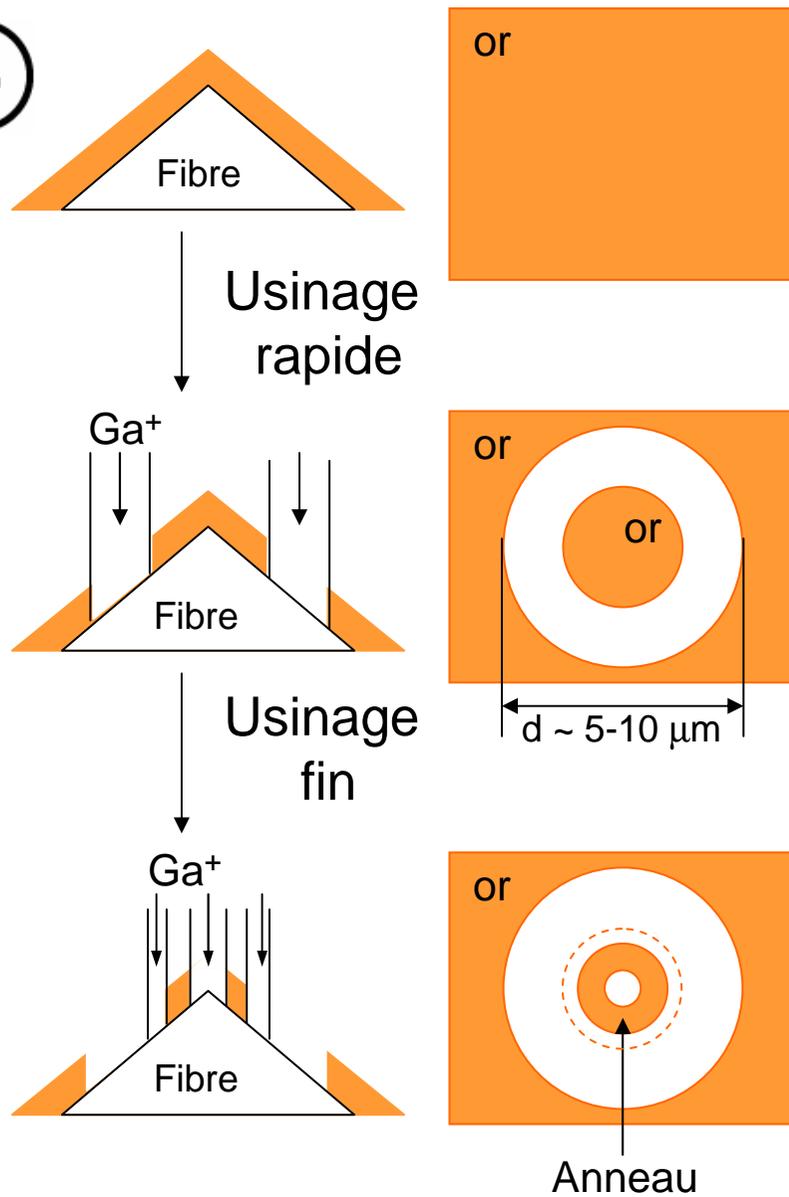
Dépôt d'or : $e = 115 \text{ nm}$



Images MEB

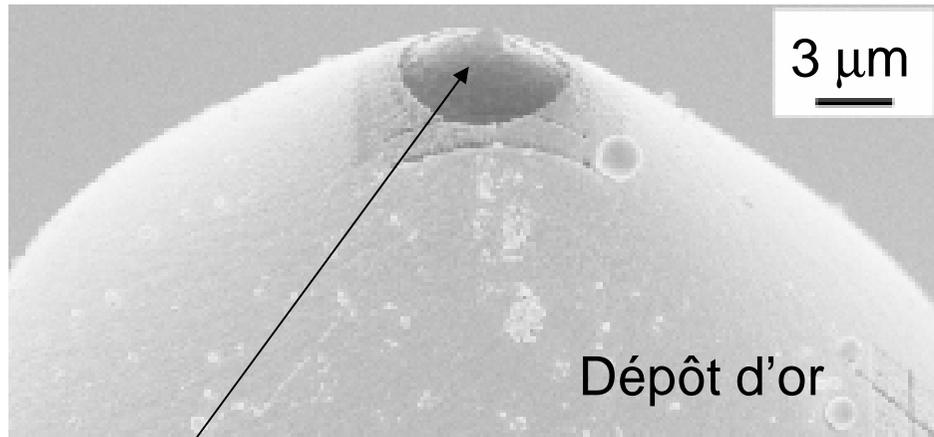
Usinage FIB

④

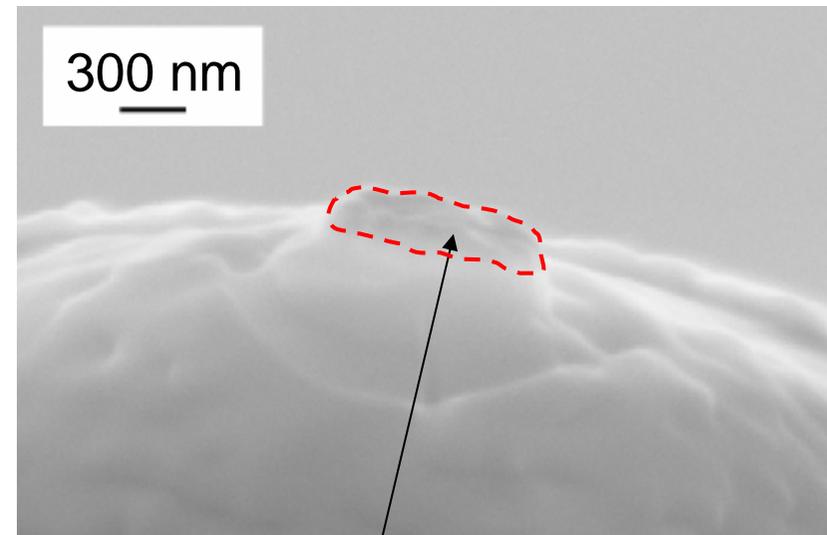
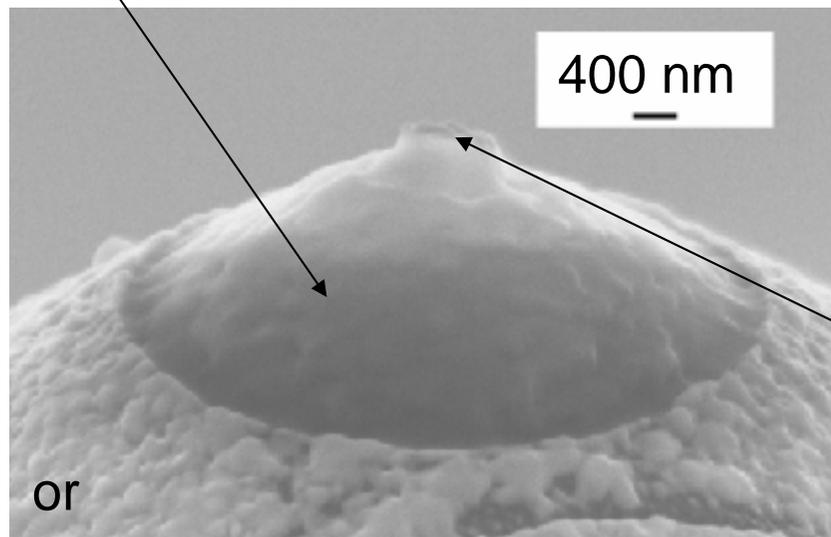


Substrat non plan :
extrémité de fibre optique

Nano-antennes annulaires

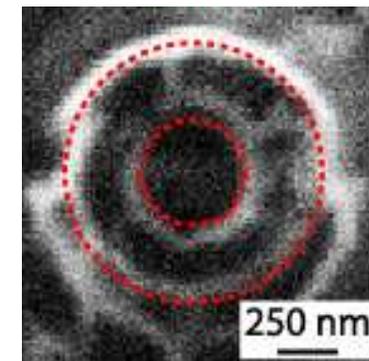
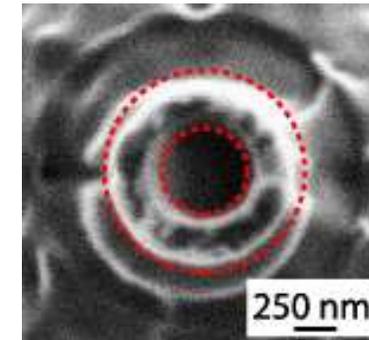
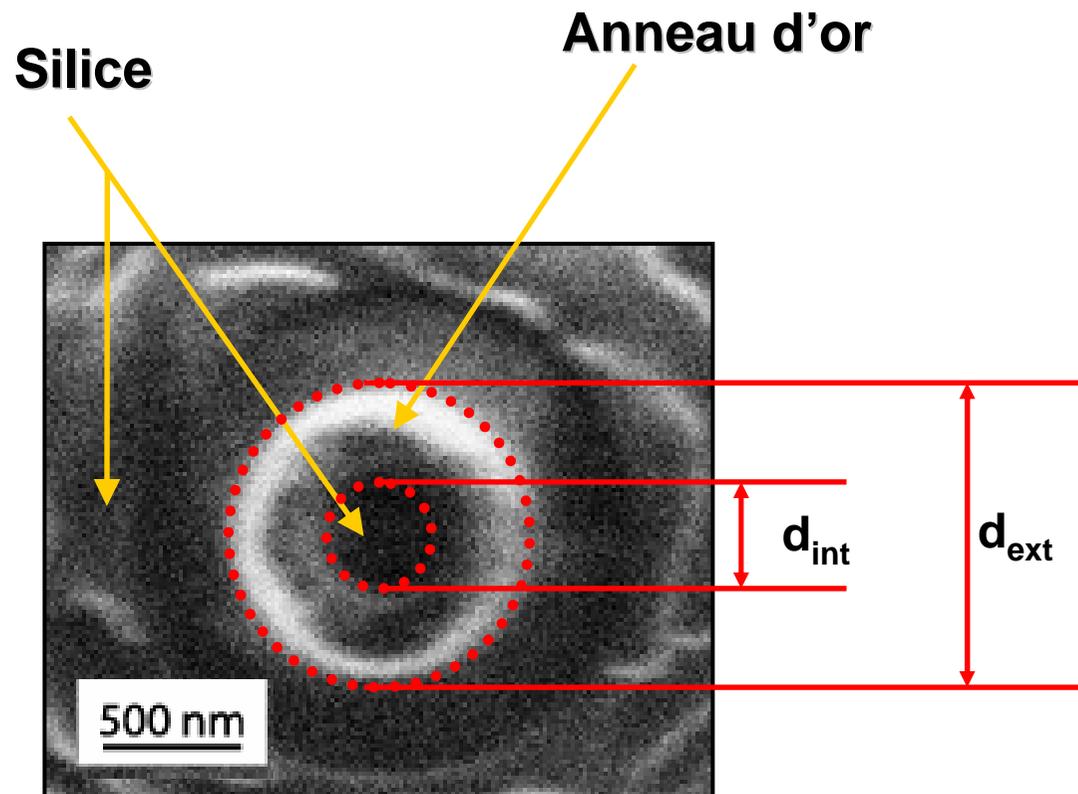


Silice



Images MEB (vues de profil)

Nano-antennes annulaires



Zoom sur l'extrémité :

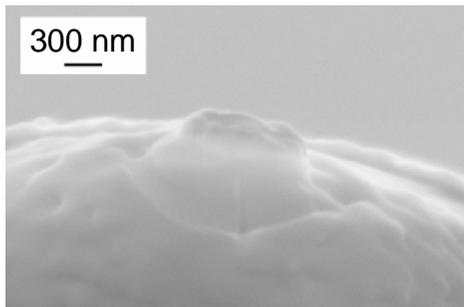
$$d_{ext} = 1 \mu\text{m}$$

$$d_{int} = 400 \text{ nm}$$

$$e = 115 \text{ nm}$$

Images MEB (vues de face)

Fabrication d'une nanostructure

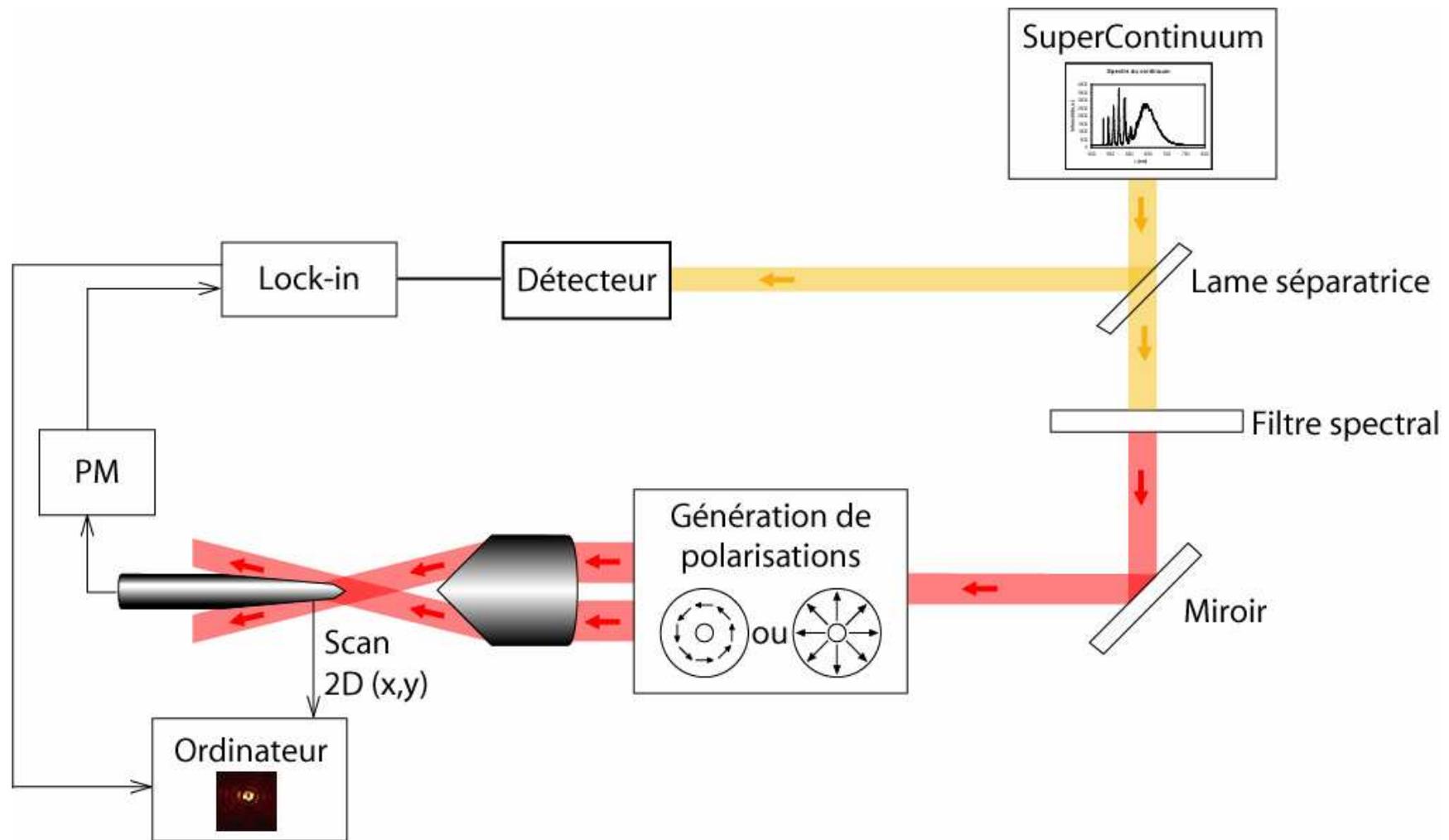


- usinage à l'extrémité d'un micro-axicon fibré
- structure simple : l'anneau
- centrage de la structure
- dimensions spécifiques : submicrométriques

Plan

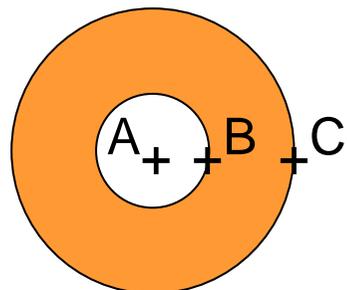
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Montage de caractérisation



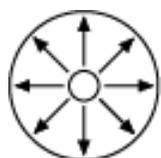
Objets tests : Faisceaux de Bessel
- polarisation radiale ou orthoradiale
- $532 \text{ nm} < \lambda < 700 \text{ nm}$

Etude théorique : simulations spectrales

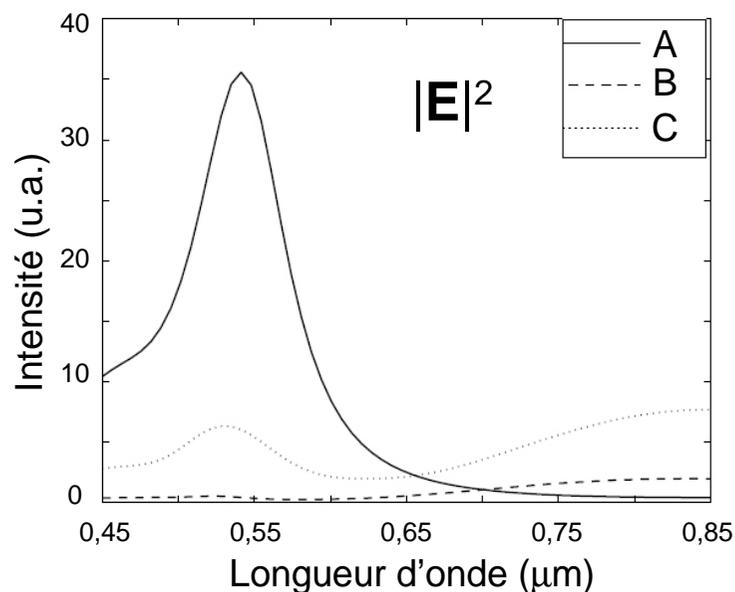


Anneau d'or

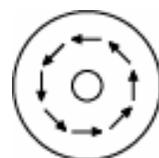
$d_{\text{int}} = 400 \text{ nm}$; $d_{\text{ext}} = 1 \mu\text{m}$;
 $e = 100 \text{ nm}$



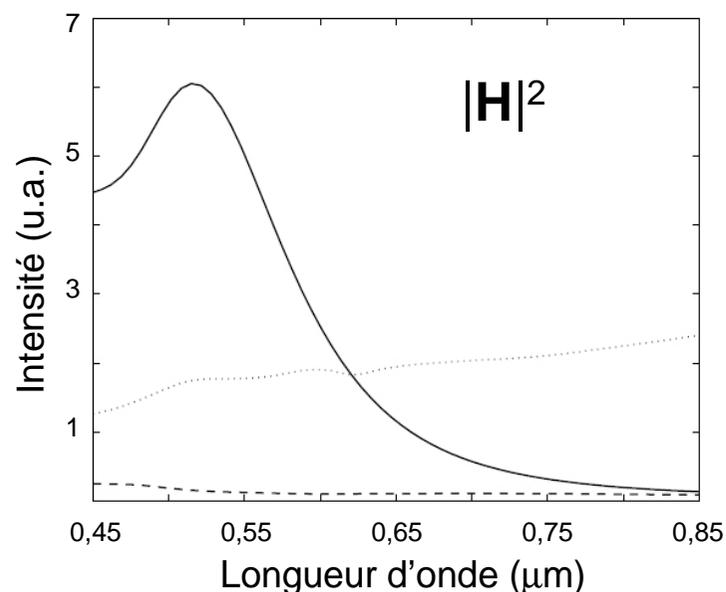
Polarisation **radiale**



($\lambda_{\text{res}} = 540 \text{ nm}$)

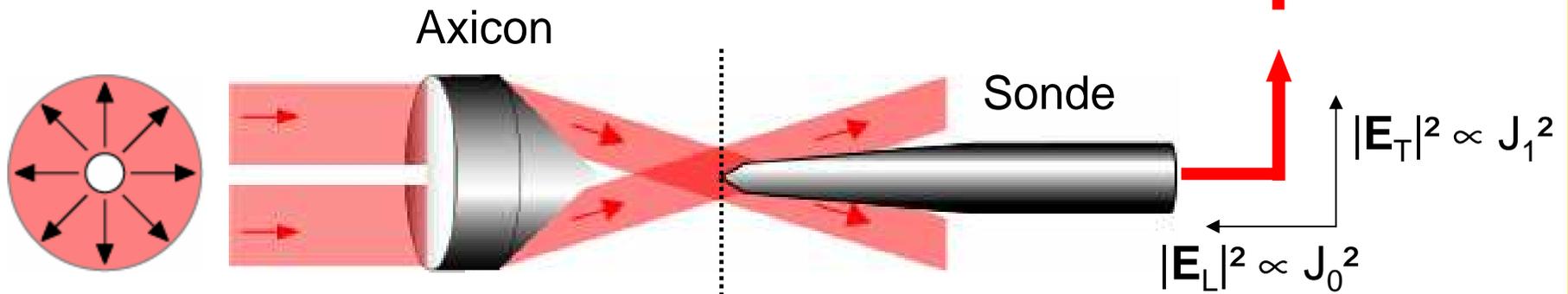


Polarisation **orthoradiale**

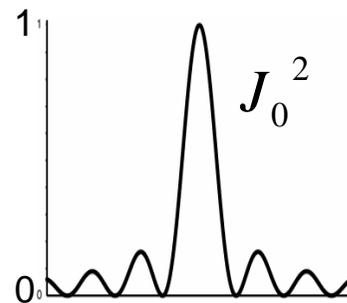
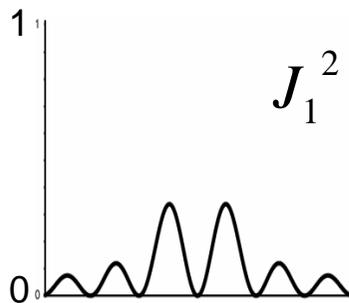
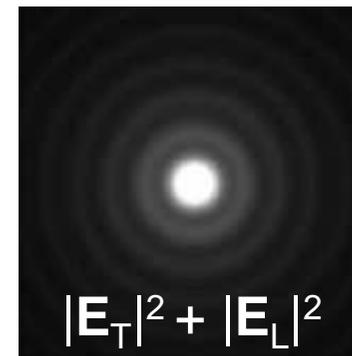
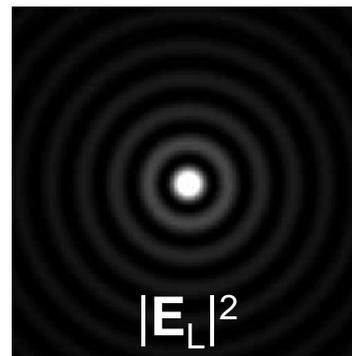
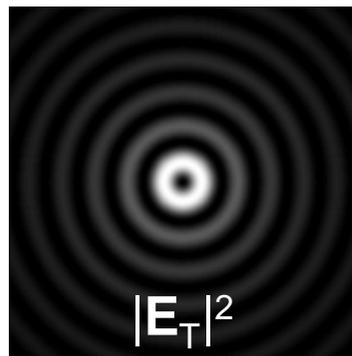


($\lambda_{\text{res}} = 514 \text{ nm}$)

Polarisation radiale $|H_L|=0$



Objet théorique



Profils d'intensité

Caractérisation (radiale)

Pointe diélectrique, $\lambda = 632 \text{ nm}$

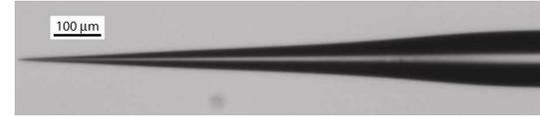
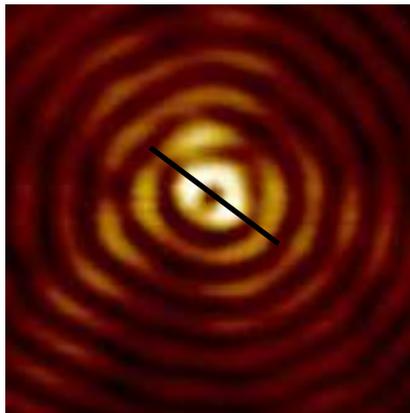
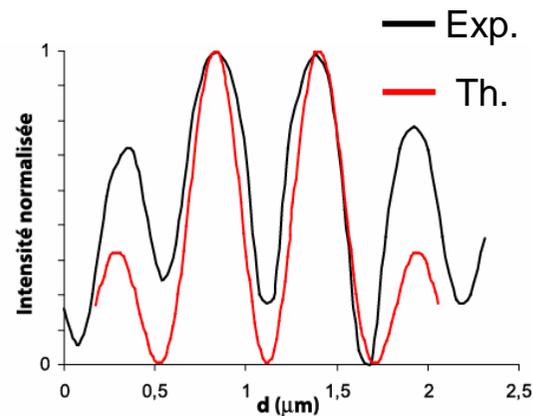


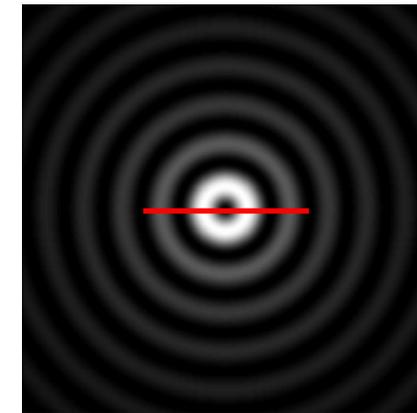
Image optique



Profils d'intensité



Théorie



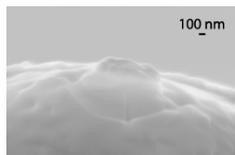
$$|\mathbf{E}_T|^2$$

Images identiques à toutes longueurs d'onde.

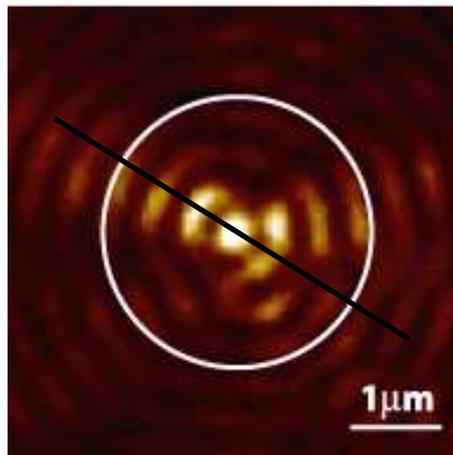
Non restitution de la composante longitudinale
Accès à $|\mathbf{E}_T|^2$

Caractérisation (radiale)

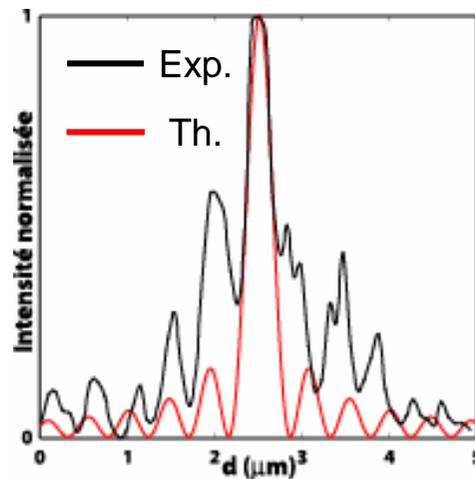
Pointe A
 $\lambda_{\text{res}} = 603 \text{ nm}$



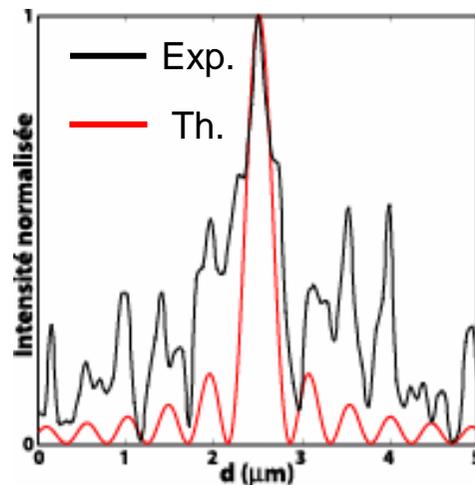
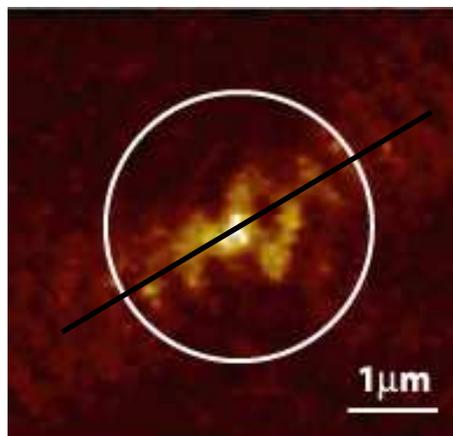
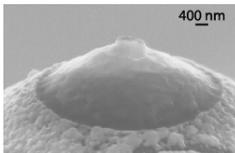
Images optiques



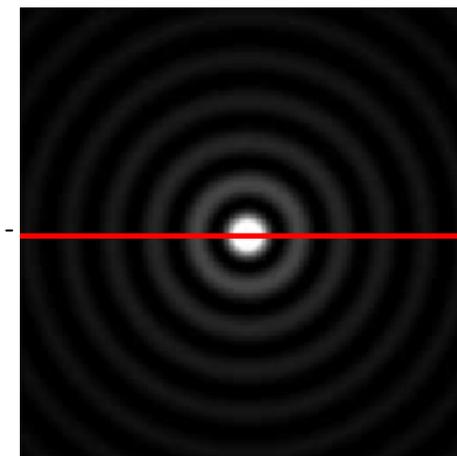
Profils d'intensité



Pointe A'
 $\lambda_{\text{res}} = 559 \text{ nm}$



Théorie



$$|E_L|^2$$



Mode plasmon

Caractérisation (radiale)

Pointe A'
 $\lambda = 588 \text{ nm}$

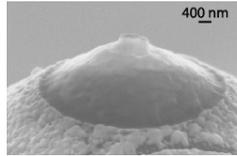
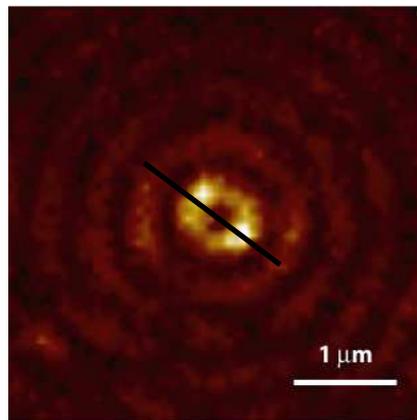
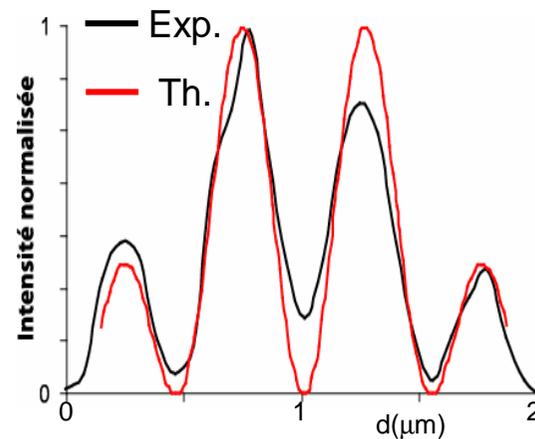


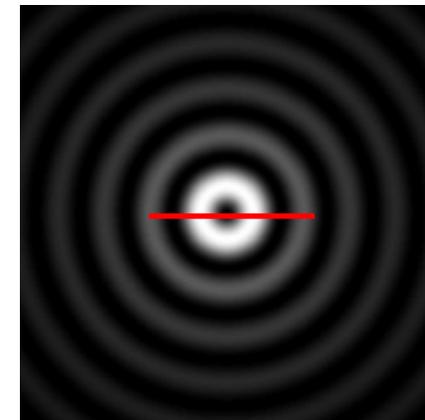
Image optique



Profils d'intensité



Théorie



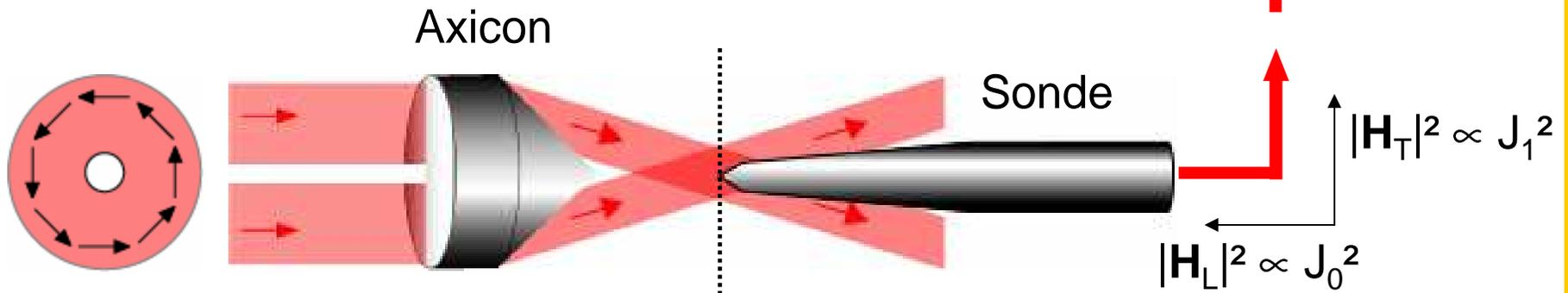
$$|E_T|^2$$

Résumé : Polarisation radiale

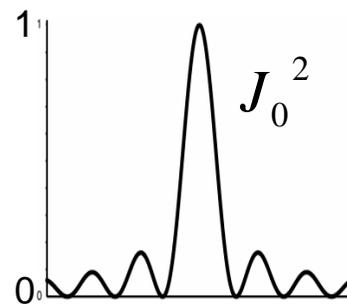
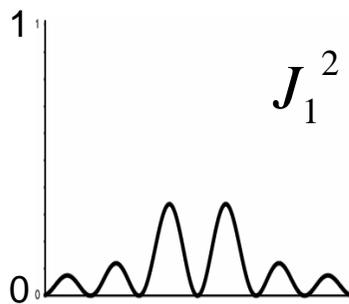
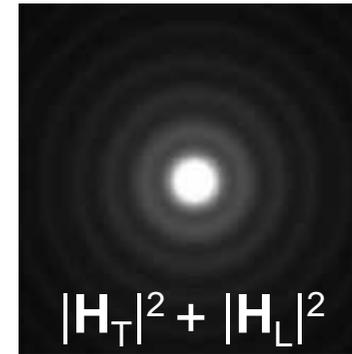
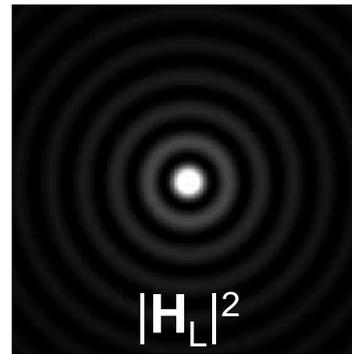
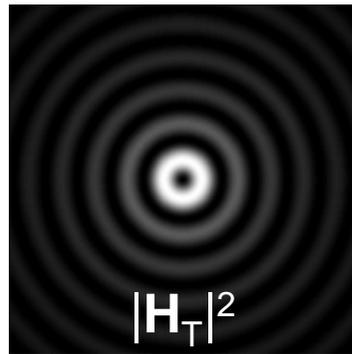
Hors résonance \longrightarrow Détection de $|E_T|^2$

A la résonance \longrightarrow Détection de $|E_L|^2 \longrightarrow$ **Mode plasmon**

Polarisation orthoradiale $|E_L|=0$



Objet théorique



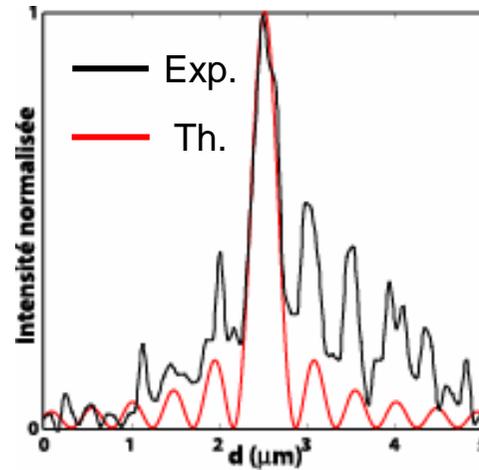
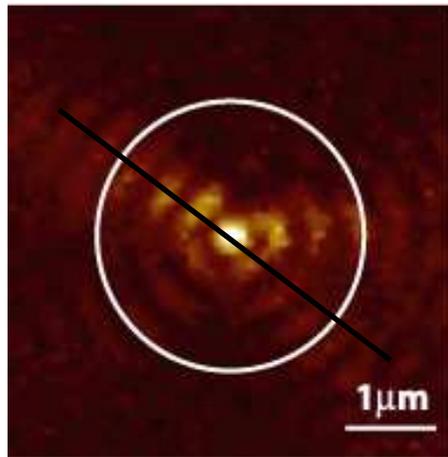
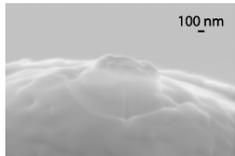
Profils d'intensité

Caractérisation (orthoradiale)

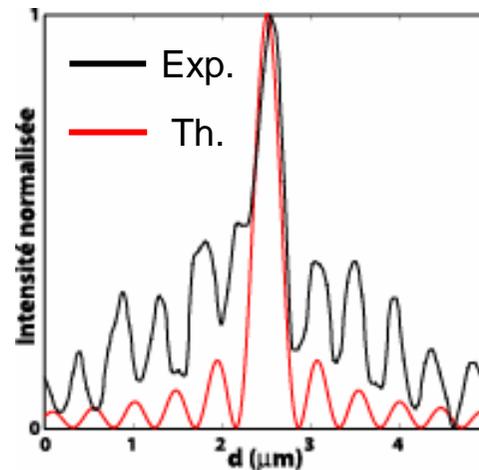
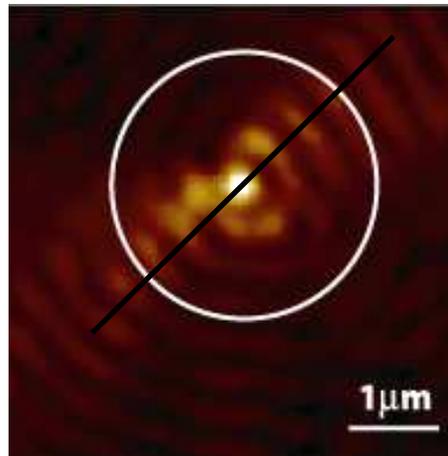
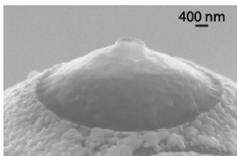
Images optiques

Profils d'intensité

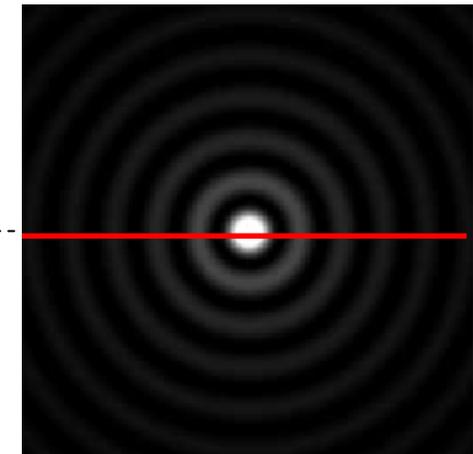
Pointe A
 $\lambda_{\text{res}} = 603 \text{ nm}$



Pointe A'
 $\lambda_{\text{res}} = 559 \text{ nm}$



Théorie



$$|H_L|^2$$



Inductance optique

Caractérisation (orthoradiale)

Pointe A'
 $\lambda = 588 \text{ nm}$

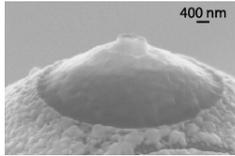
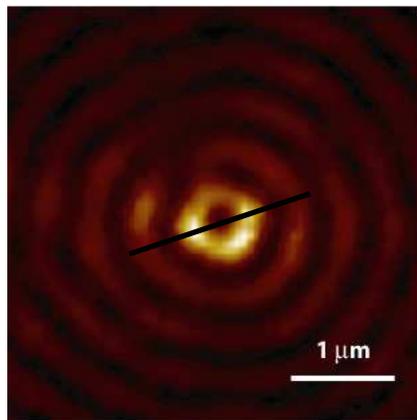
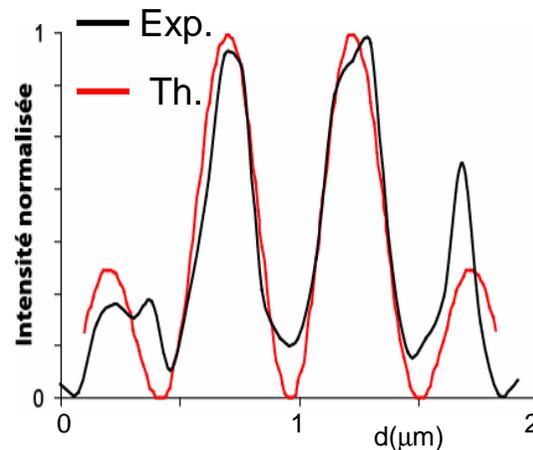


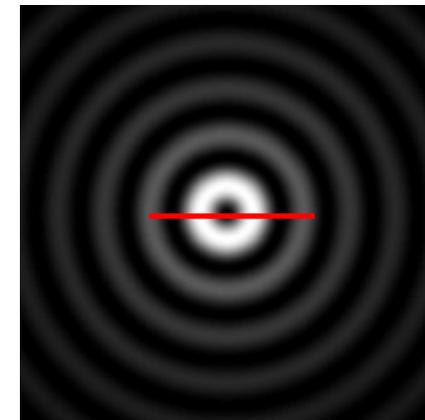
Image optique



Profils d'intensité



Théorie



$$|\mathbf{H}_T|^2$$

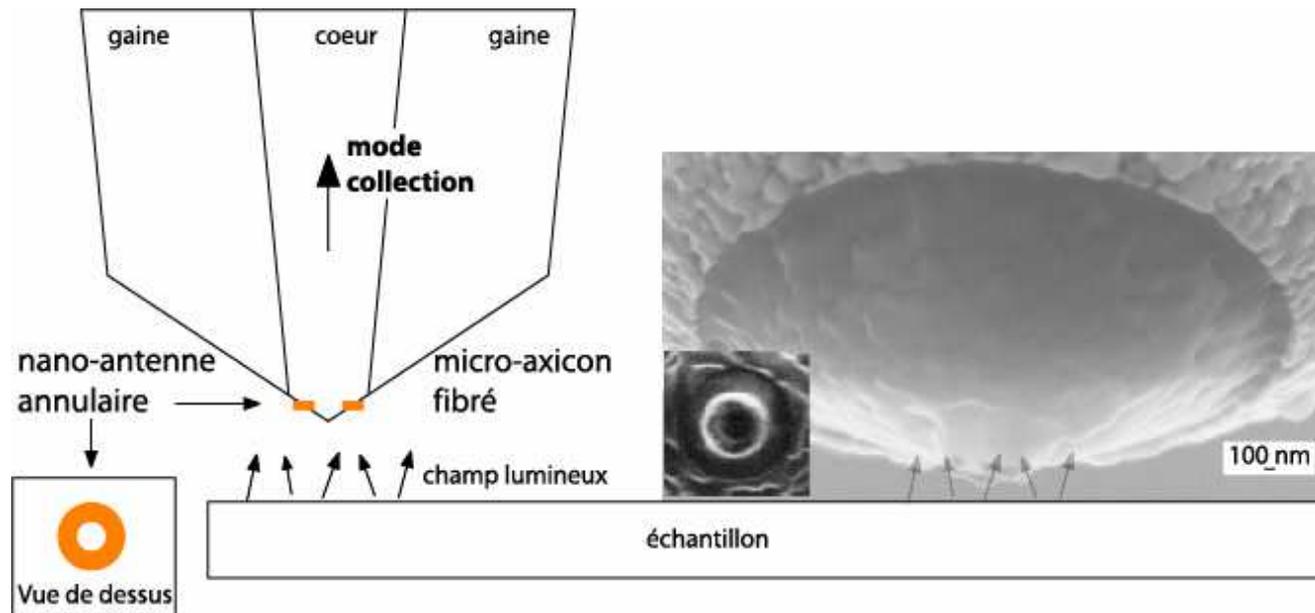
Résumé : Polarisation orthoradiale

Hors résonance \longrightarrow Détection de $|\mathbf{H}_T|^2$

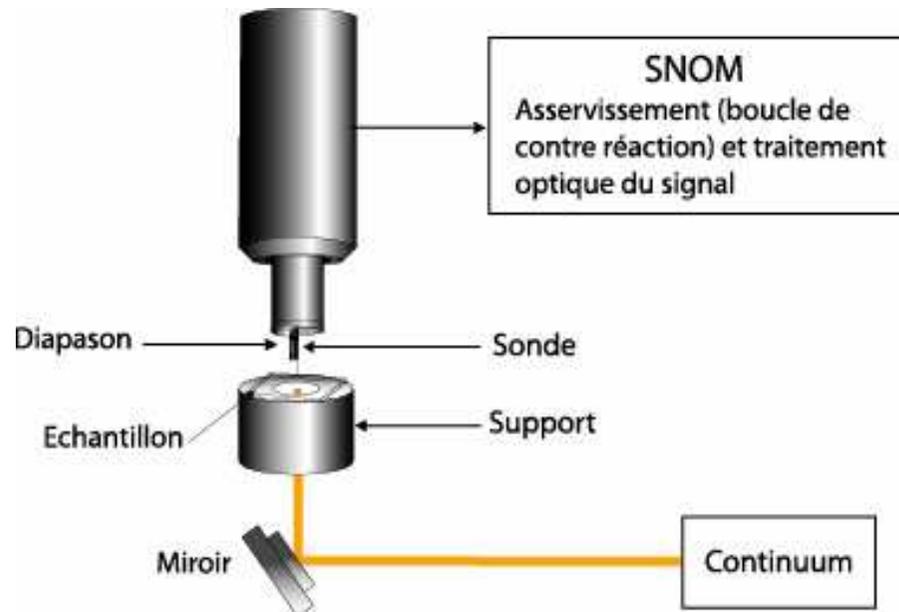
A la résonance \longrightarrow Détection de $|\mathbf{H}_L|^2$

**Inductance
optique**

Application

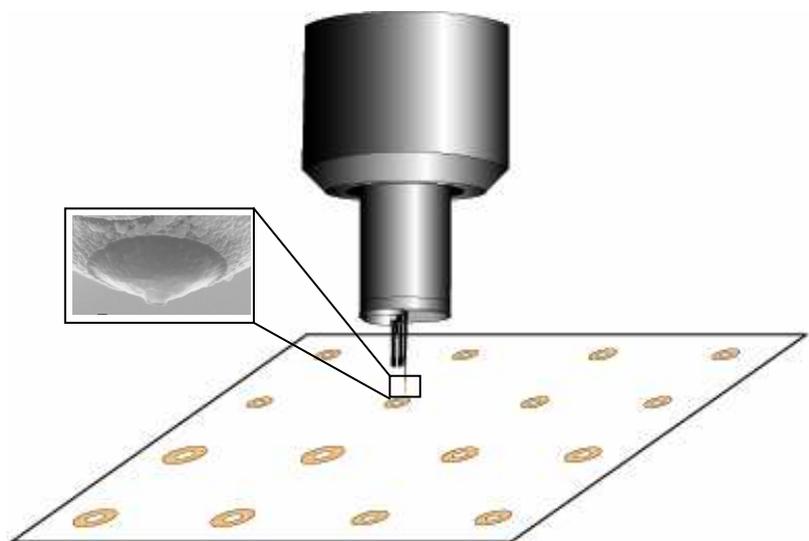


Principe



Montage

Premiers tests



Matrice d'anneaux

Image optique

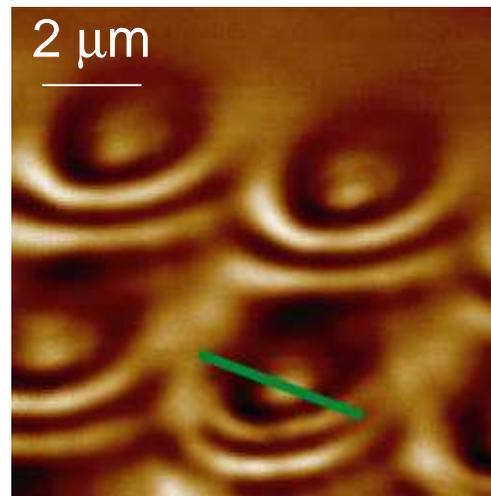
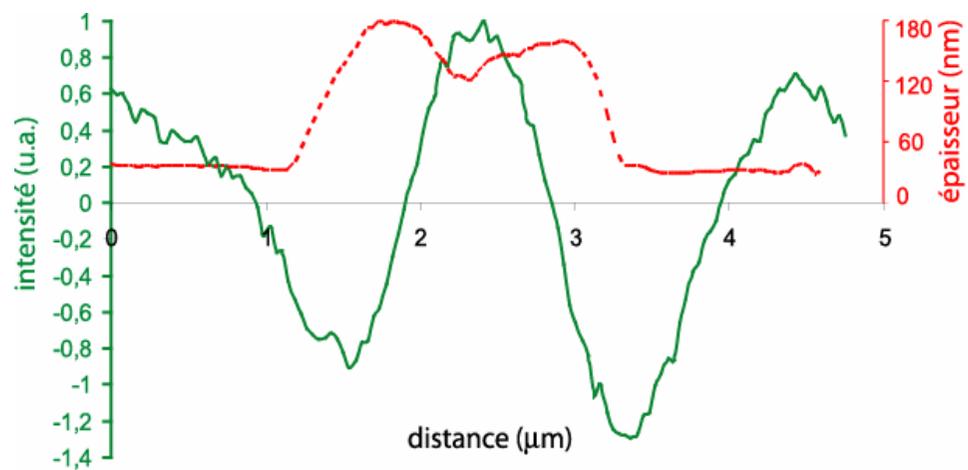
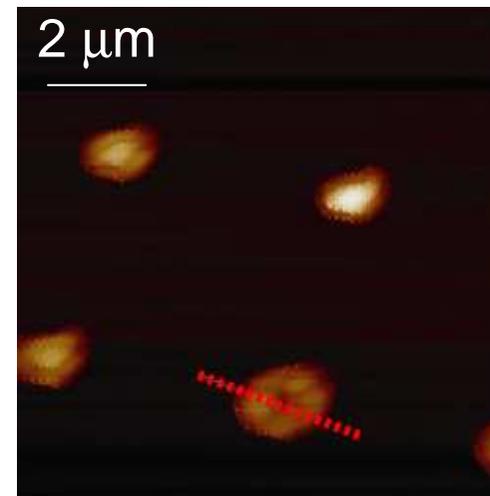


Image topographique

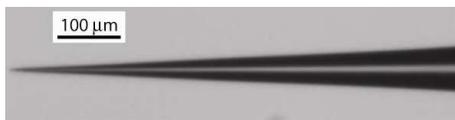
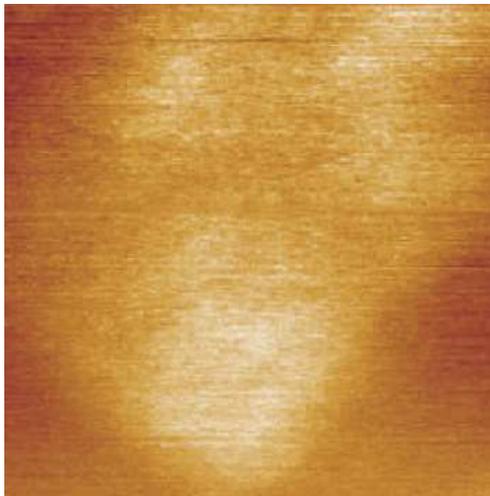


Coupes

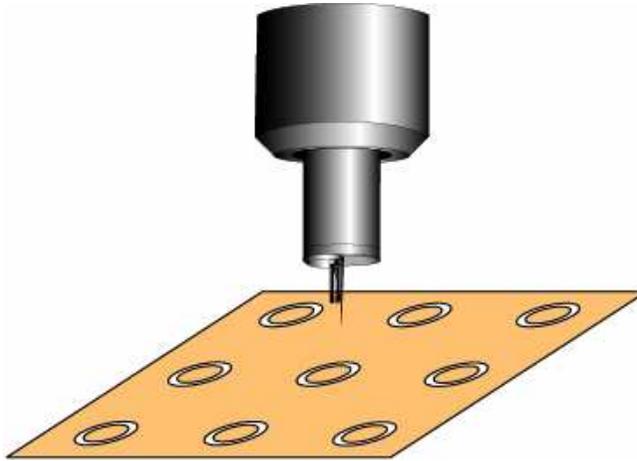
➔ Sonde opérationnelle

Premiers tests

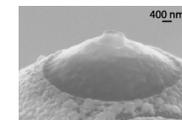
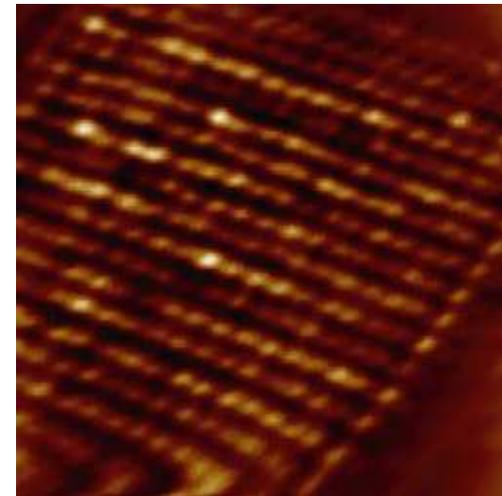
Images optiques ($13 \times 13 \mu\text{m}^2$)



Pointe diélectrique



Structures coaxiales



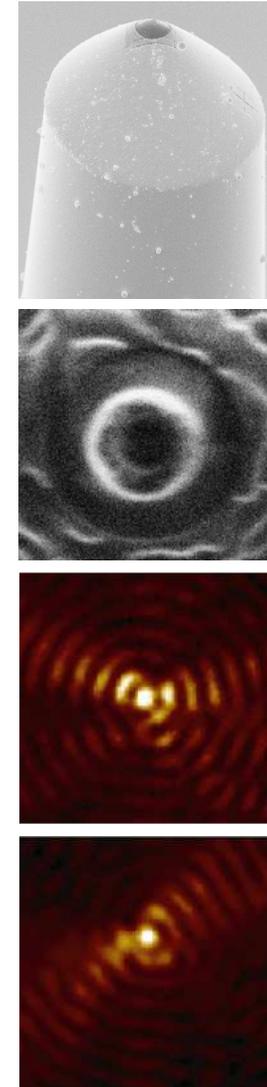
Nano-antenne

Plan

- Microscopie en champ proche & Antennes
 - les sondes
 - les antennes
 - les faisceaux de Bessel polarisés
 - choix de l'antenne
- Techniques de fabrication
 - thermo-étirage & autres techniques
 - polissage & métallisation
 - usinage FIB
- Validation & Tests
 - caractérisation des nano-antennes
 - premiers tests en imagerie
- Conclusion & Perspectives

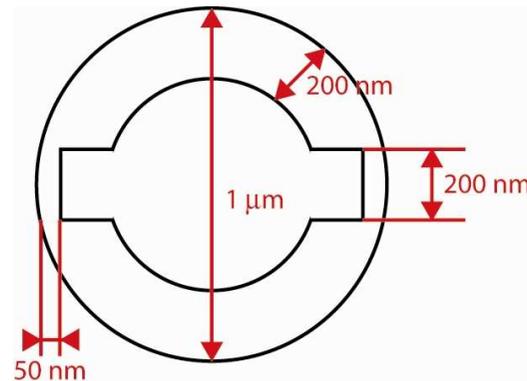
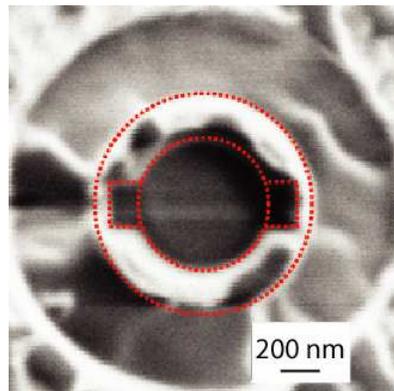
Conclusion

- Intégration d'une nano-antenne à l'extrémité d'un micro-axicon fibré
- Discrimination de **E** et **H**
- Concordance avec la théorie
- Sonde fonctionnelle adaptée



Perspectives

- Modifier les paramètres de l'anneau
- Utilisation des sondes en condition
- SQUID



- Microscopie basse température
- Métamatériaux



Micro et nano-antennes adaptées à la microscopie champ proche et à l'imagerie haute résolution

MERCI DE VOTRE ATTENTION

